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THE IMPACT OF ENGINEERING RESEARCH CENTERS ON INSTITUTIONAL AND CULTURAL CHANGE IN PARTICIPATING UNIVERSITIES

FINAL REPORT

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Foreword

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Executive Summary

Overview

This report is one of a series of studies being conducted by SRI International on the impacts and futures of individual Engineering Research Centers (ERCs). Reflecting widespread perceptions in the early 1980s that "cultural" barriers impeded effective collaboration between universities and industry, it was implicit that programs supporting university–industry–government collaborative R&D centers, such as ERCs, were intended to alter individual and collective norms and practices on university campuses in part. Because academic engineering research and education were seen as contributing little to the revitalization of the international economic competitiveness of the United States, an emphasis on changing the institutional and cultural norms of academe permeates the design of the ERC Program, and the criteria by which ERC proposals are reviewed: the impact of this dimension of such centers has been given only passing attention in previous studies.

This study focuses on the degree to which ERCs have produced or contributed to changes in institutional and cultural norms of academic engineering research, education, and technology transfer in the universities that host ERCs by examining institutional and cultural changes at two levels:

1) identifying changes that affected faculty, students, and academic units directly involved in the ERC; and

2) identifying changes in the larger university setting, i.e., in the larger set of policies, practices, and behaviors of other parts of the university – the "spillover" or "externality" effects of the ERCs.

The concept of "institutional change" in the context of this study includes changes in a host institution's organizational structure and in its formal and informal policies and practices related to research, education, and technology transfer. Operationally, "institutional change" refers to actions such as the establishment of new types of courses or degree programs, changes in promotion and tenure requirements or policies, changes in intellectual property and technology transfer policies and strategies, and policies directed at creating or supporting multi-disciplinary research centers

In 1985, NSF stated that the ERC Program's goal as to "further the development of fundamental knowledge in engineering fields that will enhance the competitiveness of U.S. industry and prepare engineers to contribute through better engineering practice." ERCs were directed at overcoming shortcomings in the pattern of education and research, including an overemphasis on analytical studies at the expense of experimental research, the preference for disciplinary rather than cross-disciplinary research and systems engineering, and the paucity of instrumentation and larger scale facilities that would permit the testing and operation of small-scale prototype systems. Many believed that academic engineering research and education were becoming increasingly separated from the dominant modes of operation of U.S. industry.

ERCs were to address the need to focus on the "systems aspects" of engineering research and education, where research took a "cross-disciplinary approach in which engineers and scientists from separate disciplines work as a team to solve problems bearing directly on the needs of industry or society," and education provided an understanding of "how systems are designed, manufactured, and supported in the field." Three specifics should characterize their research and education activities:

1) research conducted was to be strategically planned and directed at problems that industry could not "meet because it lacked the fundamental engineering knowledge";

2) cross-disciplinary activities were to be an integral part of operations – not as an end in itself, but because "the problems of engineering practice rarely fall neatly within the confines of individual academic disciplines";

3) active intellectual involvement of industry was essential to forge strong links between academic engineering research and education.

Study Design

The study was limited to the 17 ERCs that had been in existence for at least ten years at the study's inception, at least partly because there appeared to be fewer concurrent influences calling for change to be considered than have subsequently developed in the 1990s. Information on all 17 was obtained from their annual reports and related documents, as well as from site visits made in connection with an earlier study with a different primary objective. A stratified random sample of ten host universities was selected for a new set of site visits, including a mix of public and private, Carnegie Research I and II universities, and the only Doctoral II institution hosting an ERC. Table I lists the ten universities visited for this study. The six schools visited only for the previous study were Lehigh University, the Ohio State University, the University of Illinois, Duke University, North Carolina State University, the University of Minnesota. (Carnegie Mellon University has two ERCs: the focus in this study was on the Data Storage Systems Center, not the Engineering Design Center.)

The purpose of the site visits during this study was to determine the extent to which academic administrators, faculty, professional staff, and students could point to verifiable changes in institutional policies, practices, and norms that relate to the specific objectives of the

ERC program and were attributable to the ERC and its activities. The study's coverage included both those academic units directly associated with or involved with the ERC and the larger university of which they are a part. The broadened coverage was intended to determine the

Table I
ERC Site Visits Conducted for This Study

Lead University	Center	Region	Public-Private	Carnegie Classification
Brigham Young University	Advanced Combsution Engineering Research Center	Southwest	Private	Research II
Carnegie Mellon University	Data Storage Systems Center	Northeast	Private	Research I
Massachusetts Institute of Technology	Bioprocessing Engineering Research Center	Northeast	Private	Research I
Mississippi State University	Center for Computational Field Simulation	Southeast	Public	Research II
Montana State University	Center for Biofilm Engineering	Northwest	Public	Doctorate
Purdue University	Center for Collaborative Manufacturing*	Midwest	Public	Research I
Texas A&M University	Offshore Technology Research Center	Southwest	Public	Research I
University of Colorado	Optoelectronic Computing Systems Center	Southwest	Public	Research I
University of Maryland	Institute for Systems Research	Northeast	Public	Research I

*formerly Center for Intelligent Manufacturing Systems

impact on research, education, and technology transfer for other academic or research units within the university. The extent and spread of the institutional and cultural changes generated by ERC activities depends in part on the number of faculty and academic units directly involved in a center's activities, and indirectly on organizational influences that determine the paths and processes by which changes brought about by the ERC spread to other faculty and academic units. In addition, the "cultures" surrounding different bodies of knowledge – that is, academic disciplines – have been found to vary significantly across a given university, a factor that had to be taken into consideration.

This perspective about the possible multiple locus of institutional and cultural change shaped the identification of academic administrators, faculty, and students to be interviewed. The most direct (and largest) impacts were expected in the departments and colleges that directly participated in the ERCs, and interviews focused on those academic units (colleges/departments). However, ERCs meant that host universities come to grips with the issues associated with the introduction of a large-scale interdisciplinary research center into systems that have historically been departmentally based. Institutional adaptations to these situations affect the "climate for research" for faculty across the campus. To capture these possibly broader effects, as well as to obtain as full an account of what the institutional culture was at the time an ERC was established within a university, interviews also were scheduled with senior academic officials, including provosts and vice presidents for research – even former administrators no longer with the host university.

Findings

The ERCs had a multiplicity of diverse impacts on their host university campuses, although it was often hard to separate the ERCs' influence from other influences on engineering (as well as other) research and education during the period of their existence. Findings about the impacts are organized on the basis of major NSF program objectives.

Engineered Systems

The generic objective of achieving system-level goals was shared widely among participants at every host institution, but interviews seemed to indicate that the terms "engineered systems" and "systems approach" meant all things to all people. Consequently the specific definition and operationalization of the concept varied both within and across host institutions. A few of the Centers, such as Carnegie Mellon's DSSC and the Missippi ERC, had an engineered systems orientation viewed internally as the core feature of the ERC that had led to impacts in other areas. More frequently, Centers reported difficulty in formulating what constituted an appropriate engineered system that met NSF agreement. This was particularly true of Centers that have more conceptually based research agendas, such as Maryland's Systems Research ERC. Regardless of the degree to which the engineered systems approach was embraced within the ERC, it had negligible effects on other activities, even within the College of Engineering.

Strategic Planning

A key distinguishing feature of an ERC is strategic planning of the research, education, and technology development and commercialization activities of the Center. The ERCs themselves are required to develop their initial strategic plans in the first 3 months and to submit annual updates of their strategic plans as part of their Annual Report to NSF. In the vast majority of cases, the Centers had learned to value this planning process as a sufficiently important determinant of their future research direction that it remained a key management tool even when it was no longer required once the Center's ERC Program funding had come to a close. However, even in cases where departments, colleges, and the host university's central administration engaged in voluntary or required planning exercises, the ERC was not regarded as an influence. This was not surprising because in most cases, higher level planning processes had been instituted prior to the award of the ERC, and the ERC's process had limited applicability outside of the context of cross-disciplinary engineering center research operations.

Interdisciplinarity

Engineering Research Centers contributed significantly to the development of interdisciplinary research and education at each of the 16 institutions hosting the Centers in this study, primarily within Colleges of Engineering, and most extensively in the departments most closely associated with the ERCs. Increased acceptance and valuation of the formal structure required for interdisciplinary research centers and of the norms of collaborative, cross-disciplinary research was found even on campuses that had been historically open to cross-unit research. A common theme was that the ERCs demonstrated the feasibility of large-scale (relative to prior institutional experiences) collaborative, interdisciplinary research, as well as interdisciplinary instructional programs that contributed to the development of new technologies, such as biofilm engineering. Participating faculty reported that the interdisciplinary orientation had contributed positively to their research. Centers were perceived to have improved the overall research performance of host institutions and had stimulated some host institutions to devise strategies emphasizing interdisciplinary research centers to promote institutional excellence in niche areas and compete for outside funding. However, because ERCs financed as well as advocated interdisciplinary research, there was concern that, despite continuing interest, the amount of such research would decline without continuing ERC core funding.

The thrust towards acceptance of the interdisciplinary mode of research and education promoted by the ERCs encountered several obstacles that ranged from serious hindrance to the inspiration of new institutional policies and arrangements. Impacts thereby extended in varying degrees to other colleges which participated in the ERCs, to strategies and priorities set by central administrations, and to university-wide policies related to promotion and tenure, allocation of indirect cost recovery funds, and management of specialized research facilities.

The allocation of indirect cost recovery (ICR) funds attributable to ERC activities was often an issue in its relationship to other campus units. Universities differ markedly in their policies towards distribution of these funds. However they may be channeled, ICR funds are eagerly sought after by academic units. Several features of the ERC Program caused disagreements related to the distribution of ICR funds. The size and prestige associated with an ERC award gave rise to new organizational and reporting relationships between central administrations and ERCs, at times giving the ERCs and their directors greater autonomy relative to deans and departments than had previously existed institutionally. Some universities committed portions of the indirect cost funds derived from the ERC budget back to the ERC to demonstrate institutional commitment in the competition for an ERC, altering control of funds from deans and department heads to center directors. ERCs also controlled sizeable amounts of money from the NSF award and funding from industry and other sponsors of ERC research and educational activities. Where ERC awards represented a large proportion of external research funding, the stakes over whether these funds would be allocated for use by the ERC or distributed to the college were high. Conflicts between ERC Directors and deans or departments often rooted in the entrepreneurial character of the effort to develop a winning proposal and start up a new entity on campus.

The interdisciplinary and collaborative nature of ERC research and education runs counter to traditional notions of individual faculty research results published in a well-defined set of disciplinary-based journals. Hosting an ERC thus required a university to consider and often to adjust its norms and policies for promotion and tenure. Deans, department heads, and ERC directors often reported having to “educate” P&T committees about the emergence of collaborative research and publication. Usually a balance was struck, often informally, between a threshold of departmental work and a commitment to ERC research, although some universities did formal restatements of P&T requirements. ERC Directors are often influential in the P&T process, and while a few junior faculty were reported to have been discouraged from participating, few ERC participants failed to attain tenure. In many cases, the ERC participation was perceived as an advantage.

Education

Education was the area in which the most widely spread impacts of ERCs were discernible on the 16 university campuses covered in this study. Although the effects of ERCs *per se* were often difficult to unravel from the many concurrent influences pressing for change in science and engineering education during the last decade, particularly at the undergraduate level, in every case but one at least some changes in the direction of increased interdisciplinary exposure, team-based research experience, industry interaction, and/or undergraduate involvement in research was at least in part attributed to the models set forth by the new curricula and courses, Research Experiences for Undergraduates (REU) programs, seminars and workshops, and other educational activities initiated by the ERCs. The changes attributable to the ERCs were most clearly evident in those departments with direct participation in the Centers, but generally were also apparent to at least some degree throughout the colleges of engineering. In some cases, the educational impacts of the ERCs were experienced as campus-wide phenomena, literally affecting practically all colleges and departments throughout the university.

Virtually all of the ERCs included in this study have created new courses and modified existing courses at both the undergraduate and graduate levels. Most of these courses were designed to reflect the interdisciplinary, systems-oriented research undertaken by the Center. Enrollment in these courses by students not otherwise directly exposed to the ERC often served as a multiplier of the number of students the ERC was able to influence directly. In addition, many Centers have also developed or spurred the development of entire new degree programs. New degree programs are often cross-school, so courses are cross-listed, reflecting curricular changes broader than in engineering. The Maryland ERC, for example, developed a new M.S. in systems engineering, while the Purdue ERC has developed an M.S. option in manufacturing.

The active involvement of undergraduate students in Center research activities is a requirement of the ERC Program. Each of the ERCs therefore has at least one program through which undergraduates from their own university participate in Center research. Programs for students within their own institutions generally entail students working in research laboratories under the direction of ERC faculty and/or graduate student mentors. Many ERCs also have summer REU programs in which undergraduates from other universities join undergraduates from the center institutions and participate in the Center's research. While the ERC efforts came at a time when other forces were pushing engineering education in similar directions, there were a few cases in which the ERC was cited as the only locus for undergraduates to gain exposure to research. Industry was reported to find students from these programs better prepared for jobs in industry, and as having a better sense of what a career in industry was likely to be like, confirming other studies' findings in this regard.

Graduate student involvement in an ERC is unique in several respects. First is the degree of cross-disciplinary interaction and exposure through work on ERC research teams that generally involve faculty and students from disciplines other than their own fields of concentration. A second difference is that ERC students typically have considerably greater interaction with industry than is the norm. ERCs were often credited with serving as a major attraction in the recruitment of high quality graduate students, especially within those departments most directly involved, and graduate students generally reacted extremely favorably to the interdisciplinary course work as well as the research exposure they obtained through association with the ERC.

Industry Interaction

The ERC Program had major, discernible impacts on how universities perceived, valued, and organized their interactions with industry. The impacts on research and education built upon and helped shape the trend towards increased and closer collaboration between universities and firms throughout the 1980s, as reflected in the increased percentage of academic R&D funds supplied by industry and the spread of university-industry-government cooperative R&D centers. For institutions with a long history of involvement with industry, such as MIT, Purdue, and Carnegie-Mellon, ERCs brought a larger, more sustained level of interaction. For other institutions, such as Montana State University and Brigham Young University, the ERC created a scale of interactions that the university had not previously experienced.

The ERCs had modest impacts on the formulation of university intellectual property rights policies across the host campuses, primarily because the Bayh-Doyle Act had already set in motion a widespread, often fundamental rethinking and restructuring of the university's patent and licensing policies on most of them. However, dealings with industry also often required new understandings and negotiation skills on the part of the university's office of sponsored research projects. In their new dealings with industry, faculty at times complained that sponsored research administrators were unfamiliar with industry practices, such as fixed-price contracts and invention disclosures. More frequent and intensive interactions of the ERC with firms often created the first or early "cases" that directed the shape of a university's new IPR policies or were the specific settings about which general policies become converted into case practice.

Overall Impacts and Implications for NSF

To a considerable degree, the objectives set forth in the initial formulation and establishment of the ERC Program have entered the mainstream of discourse about the desired ends, structure, and activities of America's research universities. This trend complicates disentangling the impacts of ERCs from other convergent influences. Many of the cultural-change objectives, such as the emphasis on interdisciplinarity or increased industry interaction sought by the ERCs, accord with broader calls for reforms in the characteristics of knowledge generation and dissemination in America's research universities. These calls also echo themes in the ERCs' educational objectives towards having graduate and undergraduate students actively participate in problem-focused, interdisciplinary research projects that involve the integration of theory and practice and that also involve the participation of both faculty and industrial researchers. ERCs represent but one of a series of efforts to alter, if not the missions of research universities, then at least their functioning and outputs, both research and educational, better to meet the needs of a number of their existing constituencies – especially students – as well as those of new, or relatively more important, constituencies.

Institutional advances towards increased interdisciplinarity were observed at ERC institutions, especially in selected engineering, science and a few social science/humanities fields, but systematic advances towards interdisciplinary approaches to education and research still remain an upward struggle at many research-intensive universities, again allowing for variations among fields and universities. Although this study identified many positive impacts of ERCs on their host institutions, it would be incorrect to speak of wholesale change in the structures, activities, or norms of academic research, education, and technology transfer, whether on the part of the university or of colleges of engineering which are the immediate organizational homes of ERCs.

SRI examined a number of variables that might help explain differences observed in the degree to which ERCs had impacted their host universities along various dimensions. The first set of variables had to do with characteristics of the host institution itself, such as its Carnegie classification, size of enrollment, percentage of graduate degrees awarded in engineering, etc. The second set related more specifically to characteristics of the ERC itself, such as the number of departments involved, the degree of industry involvement, degree of undergraduate student involvement, etc. The analysis took into account the extent to which ERC-like characteristics were common or unusual in the broader institutional environment prior to the establishment of the ERC and the degree of change that appeared to have occurred since the Center's inception. It concerned not only the perceived degree of change at the broader institutional level, but also the extent to which such change might reasonably be attributed to the presence of the Center in that environment.

The analysis showed that there few, if any, structural characteristics at the institutional level itself that account for high or low impacts on the culture of the institutions more broadly. The results were widely dispersed over the various institutional types – public/private, small to extremely large, etc. The pattern was also dispersed with respect to variables associated with the ERCs themselves, but a few characteristics here seemed to be at least somewhat correlated with the degree of positive impacts. These included high prominence of the Centers' educational programs, a high degree of undergraduate involvement, a central campus location, and a high degree of administration interest in and interaction with the Center. With the small number of observations available, however, it is the dispersed pattern over almost variables that is most striking.

PART I: INTRODUCTION AND STUDY DESIGN

Introduction

This report examines the impacts of the National Science Foundation's Engineering Research Centers (ERCs) on institutional and cultural policies, practices, and norms related to research, education, and technology transfer in the universities that host ERCs.[1] The report is one of a series of studies being conducted by SRI International on the impacts and futures of individual ERCs. Two earlier SRI reports, *The Impact on Industry of Interaction with Engineering Research Centers* (Ailes, Roessner, and Feller, 1997) and *Documenting Center Graduation Paths: Second Year Report* (Ailes, Roessner, and Coward, 2000) have examined the impact of ERCs on industrial innovation and the transition experiences and future plans of the first generation of ERCs as they approached then passed the maximum eleven years of support from their original ERC awards.[2]

The impacts of the ERC Program on technological innovation have been examined directly in a series of studies by SRI and the General Accounting Office (1988), and examined indirectly in studies on the contribution of university–industry–government R&D partnership programs to technological innovation (Cohen, Florida, Randazzese, and Walsh, 1998). Reflecting an orientation toward technological innovation and economic competitiveness, these studies have focused on economic impacts, changes in the perceptions of individual center faculty members about closer involvement with industry, changes in university technology transfer and intellectual property rights policies relating to such things as patenting, licensing, and equity holdings in spin-off companies, and changes in university conflict of interest and conflict of commitment policies.

Reflecting widespread perceptions in the early 1980s that "cultural" barriers impeded effective collaboration between universities and industry (see National Science Foundation, 1982, for example), these studies have taken as a given the proposition that programs supporting university–industry–government collaborative R&D centers were intended in part to alter individual and collective norms and practices on university campuses. Changes in the value systems of faculty and their institutions toward closer collaborations between universities and industries also have received attention, most notably in studies by Blumenthal, Gluck, Louis, and Wise, 1986; Rahm, 1994; Lee, 1996; and Rubenstein, 1995. However, with few exceptions (e.g., National Academy of Sciences, 1996), accounts and assessments of the workings and impacts of university–industry–government R&D center programs have given only passing attention to institutional changes within the university resulting from the presence of centers involved in industry-university research and education collaboration. In a parallel manner, existing studies of the ERC Program have focused primarily on the contribution of centers supported under this Program to technological innovation, noting but not describing in any detailed fashion the impacts of ERC operations on the cultural norms and institutional practices and policies of participating universities.

[1] "Host" universities receive the center award from NSF. In a few cases, the center involved one or two other institutions as well, but they for the most part are not included in this study.
[2] Centers approaching the end of their original ERC award or which have already "graduated" from the Program are eligible to compete for a completely new ERC in a "substantially different" technical area.

A Focus on Institutional and Cultural Change

ERCs were created to address perceived shortcomings in the organization and performance of academic engineering research and education (National Academy of Engineering, 1983).[3] The need to engender institutional and cultural change in the way university faculty taught engineering students, the way curricula and courses were designed and offered, the degree of curricular reform involving cross-departmental and cross-school collaboration, and the characteristics (but not the intrinsic quality) of individual faculty research suffuses statements by NSF's leadership, the President's Science Advisor, the Office of Science and Technology Policy, and the National Academy of Engineering during the ERC Program's formative years. As observed in a 1990 review of the ERC program, "Within the traditional discipline-oriented structure of universities, implementing the multi-faceted mission of the ERCs entails a considerable change in customary practices and attitudes" (National Science Foundation, 1990, p. 1). These characteristics of engineering education and academic research, in turn, were held to have limited the applicability of academic engineering research and education to the technology and productivity needs of American industry. Given these traits, academic engineering research and education were seen as contributing little to the revitalization of the international economic competitiveness of the United States.

Accordingly, an emphasis on changing the institutional and cultural norms of academe permeates the design of the ERC Program, the criteria by which ERC proposals are reviewed, and annual funding decisions are made for active ERCs. This emphasis makes NSF's ERCs distinctive among the various university–industry–government R&D centers programs established in the 1980s (including NSF's own Industry/University Cooperative Research Center Program). As stated by the National Academy of Engineering in reports in 1983 and 1989, ERCs were "unique" for the following reasons: they "emphasize(d) education and the link between education and the research activities of the center; they are explicitly oriented towards problems that industry 'cannot meet effectively because it lacks the fundamental engineering knowledge' (NAE, 1983, p. 4); and they are designed to bridge the world of academic research and education with the world of engineering practice" (NAE, 1989, p. 8). No other centers, to the NAE Committee's knowledge, had "a similar purpose" (p. 7).

This study focuses on the degree to which ERCs have produced or contributed to changes in institutional and cultural norms of academic engineering research, education, and technology transfer in the universities that host ERCs. It also attempts to determine the extent to which any such changes may reasonably be attributed to the activities and presence of the ERC. The study examines institutional and cultural changes at two levels: first, it identifies changes that affected faculty, students, and academic units directly involved in the ERC; second, it identifies changes in the larger university setting. The first level aggregates the impacts of an ERC over its life history; many of these impacts are described in the annual reports of ERCs, but seldom, however, with an accompanying description of the factors and events within a university that

[3] "Two purposes underlie the Engineering Research Centers (ERCs). One is to enhance the capacities of engineering research universities to conduct cross-disciplinary research on problems of industrial importance. The other is to lessen one of several weaknesses in engineering education: an inadequate understanding by students of engineering practice, that is, the understanding of how engineering knowledge is converted by industry into societal goods and services" (NAE, 1983, p. 3).

facilitated or impeded their generation. The second level examines the "spillover" or "externality" effects of the ERCs. It treats ERCs as "exemplars," "catalysts," "role models," or "change agents" that, by presenting specific needs, pressing against existing norms, or highlighting new opportunities, induced changes in the larger set of policies, practices, and behaviors of other parts of the university. Still, it must be kept in mind that ERCs typically involve only a small percentage of the entire population of engineering faculty and students at most universities. Thus, although occasional events that impact the larger university setting are noted in the ERCs' annual reports, the university-wide impacts of ERCs on campus are largely undescribed.

The concept of "institutional change" in the context of this study includes changes in a university's (or college's) organizational structure and in its formal and informal policies and practices related to research, education, and technology transfer. Operationally, "institutional change" refers in this report to actions such as the establishment of new types of courses or degree programs, changes in promotion and tenure requirements or policies, changes in intellectual property and technology transfer policies and strategies, and policies directed at creating or supporting multi-disciplinary research centers[4].

The concept of institutional "culture" is defined as the "system of values, symbols, and shared meanings of a group... Culture governs what is of worth for a particular group and how group members should think, feel, and behave. The 'stuff' of culture includes customs and traditions, historical accounts be they mythical or actual, tacit understandings, habits, norms and expectations, common meanings associated with fixed objects and established rites, shared assumptions, and intersubjective meanings" (Sergiovanni and Corbally, 1984, p viii). Cultural change thus relates to changes in the "should" aspect of how academic administrators, faculty, and students think, feel, and behave about the purposes and content of research, educational, and industrial outreach activities.

Institutional policy and culture converge to establish the norms, formally mandated and informally accepted, as to what constitutes "best" and "acceptable" practice within the contemporary American research university. These norms affect, among other things, how individuals and groups value a range of portfolios of fundamental and applied research activities; the weight attached by department or college promotion and tenure committees to multi-authored or industry co-authored research publications, or to publications in interdisciplinary rather than disciplinary journals (within existing promotion and tenure criteria); and the treatment and standing of faculty who engage in center-based, industry-relevant cross-disciplinary research, or university-based technology transfer activities, or education reform – in Tornatzky and Bauman's words (1997), "whether they are treated as heroes or outlaws."

[4] People make different distinctions betwen cross-disciplinary, multidisciplinary, and interdisciplinary as descriptive terms. Genuinely interdisciplinary research generally implies the required involvement of two or more disciplines in a highly interactive fashion, with participants often going beyond their own disciplinary boundaries in the course of that research. Cross-disciplinary and multidisciplinary are usually looser terms that describe institutional arrangements more often than discrete, discipline-interactive research efforts. However, in general, we use the terms interchangeably herein, as did most of the interviewees consulted during this study.

ERC Program Goals

The ERC Program's goals were set forth in a series of planning documents and background studies on the conditions of U.S. engineering education and research and on reformulation of NSF's role in supporting research, education, and economic competitiveness (NAE, 1983 and 1987, and Suh, 1986). As stated in NSF's program announcement in 1985 that opened the first competition for ERCs, the Program's goal was to "further the development of fundamental knowledge in engineering fields that will enhance the competitiveness of U.S. industry and prepare engineers to contribute through better engineering practice." Although couched in somewhat different language and emphasis over time in successive rounds of competitions for new ERCs, these objectives and the "key features" of an ERC have remained stable over the 15 years of the ERC Program.

ERCs were intended to serve the dual purposes of reforming academic engineering education to produce "a new breed of engineer" for engineering practice and increasing the contribution of university-based, industrially relevant engineering research and education to America's international economic competitiveness. They were directed at overcoming shortcomings in the pattern of education and research that had evolved after World War II, specifically the perceived overemphasis in academic engineering research on engineering science and performing analysis at an abstract level rather than on solving problems or developing the fundamental knowledge necessary to do so. As laid out by The National Academy of Engineering's *Strengthening Engineering in the National Science Foundation, A View from the President of the National Academy of Engineering* (1983), a report prepared at the invitation of NSF to review the Foundation's engineering programs (McNich, 1984), these shortcomings included an overemphasis on analytical studies at the expense of experimental research, the preference for disciplinary rather than cross-disciplinary research and systems engineering, and the paucity of instrumentation and larger scale facilities that would permit the testing and operation of small-scale prototype systems. Connecting these concerns was the belief that academic engineering research and education were becoming increasingly separated from the dominant modes of operation of U.S. industry.[5] ERCs were seen by their champions as spearheading needed changes not only in curriculum but also in attitude and outlook on their respective campuses—in short, in the culture of their campuses (NRC, 1986, p. 9). In addition, ERCs were conceived as part of a new, more pro-active role on the part of NSF's new Directorate for Engineering to strengthen U.S. academic engineering research and education (National Academy of Engineering, 1985).[6]

[5] "The ERC Program is a result of the realization that our engineering schools are becoming increasingly engineering-science oriented, with greater and greater emphasis on analysis of narrowly focused topics . . . . The way we practice engineering in industry is very different from the way we teach our students. The ERCs are needed to nurture new ideas, encourage innovation, produce better-educated people, and promote stronger interaction among our institutions, including those in industry and government" (Suh, in NAE, 1986, p. 39).

[6] NAE reports called for strengthened research programs in basic engineering disciplines, development of strong interdisciplinary and systems engineering research activities and curricula, and strengthened relationships between industry and universities, particularly in design, processing, and manufacturing engineering, and development of the science base of those fields" (NAE, 1985, p. 4).

Calls for reform also emphasized the need to focus on the “systems aspects” of engineering research and education (National Research Council, 1986)[7]. A systems approach was intended as a correction to the overemphasis on science and mathematics— “theory and analysis”—in the engineering curriculum of American universities. This emphasis was held to have made students better prepared for engineering graduate study and research in specialized technical fields, but to have caused a loss in “the crucial orientation towards industrial practice and needs that traditionally helped to ensure technological eminence for the United States,” as well as a decline in the “feel” of new engineering baccalaureate, masters, and doctoral degree recipients entering industry for “systems synthesis that they once possessed” (NRC, 1986, p. 1).

A systems approach to engineering was defined as possessing the following attributes: in education, an understanding of “how systems are designed, manufactured, and supported in the field”; and in research, a “cross-disciplinary approach in which engineers and scientists from separate disciplines work as a team to solve problems bearing directly on the needs of industry or society.” Achievement of these goals required a balanced mix of hands-on experimentation, exposure to industry personnel and methods of practice, a focus on the development of generic processes and principles, and an “interdepartmental approach to design and manufacturing as an integrated whole, with no ‘wall’ between functions” (NRC, 1986, p. 2).

Also shaping the call for the combination of activities to be performed by ERCs was the view that the surge in federal support of academic basic research following the launching of Sputnik in 1957 had diverted faculty interest away from problem-focused research and from industrial sponsors. Geiger, for example, has observed that industry support of academic research doubled from 1953 to 1959, rising to 6 percent of total academic R&D in that year; industrial support continued to rise between 1959 through 1970, but since it rose more slowly than did federal support, its relative share fell to 2.6 percent in 1970: “These figures fail to convey how deeply rooted an ivory-tower mentality became on campuses during these years. The consensus even among scientists seemed to be that universities should not perform research for industry or for the defense establishment. Knowledge for its own sake was their special province, and its pursuit was not to be sullied by practical considerations” (1997, p. 364).

Several propositions followed from this perspective of the needed content of engineering research and education: first, research conducted by ERCs was to be directed at problems that industry could not “meet because it lacked the fundamental engineering knowledge”; as stated in a 1984 NAE report, “Academia’s responsibilities are not only to help provide the missing knowledge but also to understand intimately the mechanisms for—including economic and other constraints on—the conversion by industry of that knowledge” (NAE, 1984, p. 4). Second, cross-disciplinary activities were to be an integral part of an ERC’s operations; cross-disciplinarity was not to be pursued as an end in itself, but rather because “the problems of engineering practice rarely fall neatly within the confines of individual academic disciplines” (NAE, 1989, p. 5). Third, the active *intellectual* (italics, in original) involvement of industry in the center’s activities was essential if the strong links between academic engineering research and education were to be forged, including having industrial scientists and engineers actively

[7] Broadly, a system is a construct comprised of two or more elements that function in a coordinated fashion to yield some result. Engineered systems are designed and built by humans, are technical in nature, and produce a product or output that has economic and/or social value.

engaged in helping to shape ERC objectives and priorities and "working on both research and education, with both faculty and students, at both ERCs and company facilities" (NAE, 1989, p. 5).

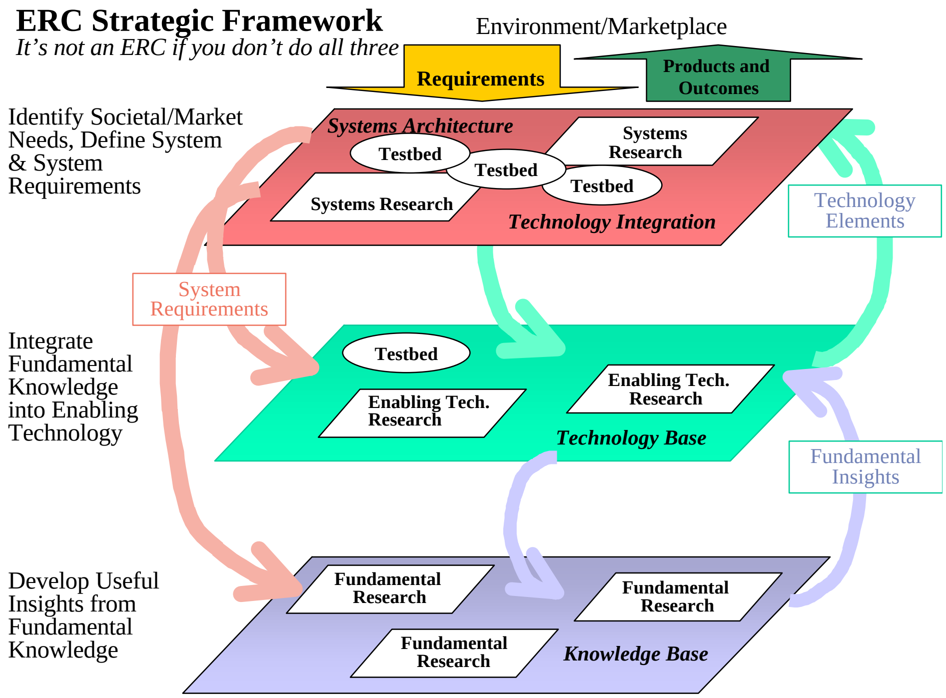
These concepts coalesced and evolved into a number of "key features" that NSF ERC Program management uses to define an ERC. They are:

- Strategic vision for advances in a **next-generation engineered system** and new generation of engineering leaders in a global economy;
- **Strategic plan** to focus and integrate the ERC to deliver;
- **Research** synthesizes engineering, science, and other disciplines, from discovery to proof-of-concept at the systems level;
- **Education program** integrating research & education producing new team culture and curriculum innovations;
- **Partnership with industry** strengthens the ERC and achieves a more effective flow of knowledge into innovation to benefit the Nation;
- Strong **leadership**; cohesive **interdisciplinary team**; diverse in gender, race, and ethnicity; infrastructure of space, experimental equipment;
- Dynamic, **flexible program for outreach** involving faculty and students from other universities and colleges;
- A **commitment** from the academic, industrial, and other partners to **substantially leverage** NSF's funds and sustain the ERC

The institutional policies, practices, and norms directly specified as Program objectives in ERC program announcements and in the criteria used in annual reviews of an ERC's progress are as follows:

- An engineered systems focus and strategic planning drives an ERC's research;
- An ERC's general organizing principle assumes total integration of research, education, and industry;
- ERCs are interdisciplinary: the engineered systems work has yielded an integration of disciplines;
- Undergraduate as well as graduate students participate in cross-disciplinary research teams and systems-level activities in ERCs;
- ERCs enhance curriculum and degree programs on the campus;
- ERCs have a strong level of financial commitment by companies and industry representatives;
- ERCs have university commitment to their continuation.

An ERC's research is intended to be organized in terms of a strategic plan driven from the systems level. NSF has developed the following three-plane diagram as an example of the ways in which ERCs integrate research conducted at three levels: fundamental, enabling technology, and systems.



Study Design

As many forms of institutional change can be assumed to involve considerable gestation periods and to occur on an incremental rather than discontinuous basis, the scope of the study was limited to those ERCs that had been in existence for at least ten years at the beginning of the study (see Table 1). The existence of multiple overlapping messages and programs similar to those found in the early 1980s ERC Program planning reports and program announcements and subsequent ones in the mid-1990s further complicates disentangling the distinctive voice of the ERCs from the larger chorus of calls for reform of the U.S. system of engineering research and education. Thus it was believed that a clearer sense of the cultural impacts of ERCs was likely to be found in the experiences of the mid- to late-1980s, when the Program was first launched and when American universities focused on international economic competitiveness but not necessarily on institutional change.

The study is based on a review of ERC annual reports and related documents from all of the above 17 ERCs, a series of site visit interviews at ten of the above ERCs, and information gleaned from site visits to all 17 ERCs as part of a recently completed parallel study to document the transition to self-sufficiency of ERCs once ERC Program support has ceased. Although there were some differences between the two studies in the character of the questions that were asked and the offices represented by the individuals interviewed, the self-sufficiency study did address aspects of institutional impacts, and relevant findings gleaned from that set of site visits are considered in the overall findings of this study.

Table I

NSF Engineering Research Centers Included in the Study

Award Year	ERC Institution	Field of Research
1985	Columbia University	Telecommunications
1985	Massachusetts Institute of Technology	Biotechnology
1985	Purdue University	Intelligent Manufacturing Systems
1985	University of Maryland	Systems Engineering
1986	Brigham Young University/University of Utah	Combustion Research
1986	Carnegie Mellon University	Design Engineering
1986	Lehigh University	Construction of Large Structures
1986	Ohio State University	Net-Shape Manufacturing
1986	University of Illinois	Microelectronics
1987	Duke University	Emerging Cardiovascular Technologies
1987	University of Colorado/Colorado State University	Optoelectronics
1988	North Carolina State University	Advanced Electronic Materials Processing
1988	Texas A&M University/University of Texas	Offshore Technology
1988	University of Minnesota	Interfacial Engineering
1989	Carnegie Mellon University	Data Storage Systems
1989	Mississippi State University	Computational Field Simulation
1989	Montana State University	Biofilm Engineering

The annual reports of individual Centers contain statements and data relating to their accomplishments relative to the ERC Program objectives. The reports, to varying degrees, contain information about how the ERC contributed to changes in university policies, and the extent to which the ERC served as a “model” for other research, educational, technology transfer, and organizational change initiatives and cultural changes elsewhere in the university. At times, too, they also point to barriers or obstacles to the effective performance of the ERC (from its perspective) that suggest that the desired degree of institutional and cultural change was not realized.

The ten Centers at which site visits were conducted directly in connection with this study were selected on the basis of a stratified random sample of the universities within which they are based (by region, public/private control, and research intensiveness) (see Table 2). The sites represent both public and private institutions and a mix of Carnegie Research I and Research II universities, plus the only ERC institution that is rated as a Doctoral II. For the most part, reflecting the national competitions used to select Centers, the awardee universities are among the more research-intensive of the nation’s higher education institutions. Still, since it is expertise in selected technology areas as well as a proposal’s ability to meet the Program’s review criteria rather than overall institutional ranking in conventional measures such as those by the National Research Council or academic R&D funds, a small number of ERCs are found in less research-intensive universities.

Table II
ERC Site Visits Conducted for This Study

Lead University	Center	Region	Public-Private	Carnegie Classification
Brigham Young University	Advanced Combsution Engineering Research Center	Southwest	Private	Research II
Carnegie Mellon University	Data Storage Systems Center	Northeast	Private	Research I
Massachusetts Institute of Technology	Bioprocessing Engineering Research Center	Northeast	Private	Research I
Mississippi State University	Center for Computational Field Simulation	Southeast	Public	Research II
Montana State University	Center for Biofilm Engineering	Northwest	Public	Doctorate
Purdue University	Center for Collaborative Manufacturing*	Midwest	Public	Research I
Texas A&M University	Offshore Technology Research Center	Southwest	Public	Research I
University of Colorado	Optoelectronic Computing Systems Center	Southwest	Public	Research I
University of Maryland	Institute for Systems Research	Northeast	Public	Research I

*formerly Center for Intelligent Manufacturing Systems

The purpose of the site visits in this study was to determine the extent to which academic administrators, faculty, professional staff, and students could point to verifiable changes in institutional policies, practices, and norms that relate to the specific objectives of the ERC program and were attributable to the ERC and its activities. A copy of the interview guide is provided in Appendix A. The study's coverage included both those academic units directly associated with or involved with the ERC and the larger university of which they are a part. The latter coverage was intended to determine the extent to which the changes generated by the ERC affected more broadly the functioning of research, education, and technology transfer for other academic or research units within the university.

ERCs typically are organized around faculty strengths within several departments in colleges of engineering, augmented by the participation of faculty in other colleges at the same institution or others participating in the center. The extent and spread of the institutional and cultural changes generated by ERC activities thus depends in part on the number of faculty and academic units directly involved in a center's activities, and indirectly on organizational influences that determine the paths and processes by which changes brought about by the ERC spread to other faculty and academic units.

Although conventional usage is to speak about "institutional change," in fact, major research universities are characterized by both the comprehensiveness of their coverage of fields of knowledge and modes of operation — research, instruction, and (for public universities, at least) output — and by work units best described by Clark's phrase, "small worlds, different worlds" (Clark, 1997). The "cultures" surrounding different bodies of knowledge — that is, academic disciplines — have been found to vary significantly across a given university.[8]

This perspective about the possible multiple locus of institutional and cultural change shaped the identification of academic administrators, faculty, and students to be interviewed. The most direct (and largest) impacts were expected in the departments and colleges that directly participated in the ERCs, with the extent and force of these impacts projected to attenuate as one moved from hard-pure to soft-applied to soft-pure. For this reason, interviews focused on the

[8] "Disciplines exhibit discernible differences in individual behavior and group action, notably between 'hard' and 'soft' subjects and 'pure' and 'applied' fields: in a simple fourfold classification, between hard-pure (physics), hard-applied (engineering), soft-pure (history), and soft-applied (social work)" (Clark, p. 24).

academic units (colleges/departments) most directly involved with the ERC, augmented by interviews with academic administrators in colleges of science, applied technology, or the equivalent.

ERCs, however, may or may not be enclaves within the larger university. Institutional and cultural aspects of ERCs, seemingly unique to the conduct of engineering research, may also impact on the larger institutional environment, thereby affecting the conduct and nature of research and education in seemingly distant disciplines and colleges. Conversely, to the extent that the practices and requirements of an ERC butt up against institutional policies, practices, and norms and the center is unable to bring about change, then the performance of the center during its life as an ERC Program-funded entity may be diluted with termination of core ERC support when the center graduates, effectively ending the distinctive modes of research, education, and interaction with industry fostered by the ERC prior to graduation.

Thus, as ERCs required that host universities come to grips with the issues associated with the introduction of a large-scale interdisciplinary research center into systems that have historically been departmentally based. Examples of stumbling blocks include return of indirect cost recovery funds; autonomy of faculty to conduct research in non-college units; reporting credit for grants and publications conducted through centers rather than departments; administrative and financial arrangements for shared equipment. The institutional adaptations to these situations affect the "climate for research" for faculty across the campus. The solution, or lack thereof, to an issue surfaced by the problems of ERC operations pressing against pre-existing policies, practices, and norms can serve to shape the general institutional environment for other centers in the social sciences and humanities. In the terms that Rosenberg used to describe the contexts within which technological innovation historically has occurred, ERCs constituted both "focusing devices" and "inducement mechanisms" on their campuses.

To capture these possibly broader effects, interviews also were scheduled with senior academic officials, including, when possible, provosts and vice presidents for research. Since the changes one might expect from an ERC likely occurred over extended periods of time, efforts were made to obtain as full an account of "baseline" conditions as possible — that is, what the institutional culture was at the time an ERC was established within a university. On several occasions, this involved follow-up interviews with administrators who were no longer with the host university.

Organization of the Report

Part II of this report focuses on the specific ERCs included in this study and their apparent cultural impacts on the institutions in which they are based. Each of the ten ERCs that were the locus of site visit interviews are first described in some detail, with the discussion organized around the following topics: background and overview, systems approach, interdisciplinarity, education, industry interaction, strategic planning, and overall impacts. These summaries are followed by a much briefer description of seven additional ERCs not visited for this study. Information on these seven was collected primarily through interviews conducted during the earlier SRI study of the transition of ERCs to self-sufficiency and, to a lesser extent, through an examination of their annual reports.

Part III presents a synopsis of findings from the study as a whole, again organized around the key ERC characteristics of interdisciplinarity, education, industry interaction, and systems approach and strategic planning, which are discussed together. Possible variables that may have influenced the degree, extent (i.e. immediate departments involved to broader spill-over effects on non-participating departments and colleges, and direction of changes noted are set forth as explanatory hypotheses. Finally, several implications for NSF policies are set forth for consideration.

PART II. THE INDIVIDUAL ERCs

Introduction

This section of this report discusses the 17 individual ERCs included in this study and their possible impacts on their home institutions. As noted previously, the 10 ERCs that were the subject of site visit interviews undertaken directly in connection with this study are described first, followed by much briefer discussions of 7 other ERCs, based on site visits conducted as part of a related study and review of their annual reports.

The discussions in this section make reference to quantitative time-line data that help provide a general context regarding the features of the different universities involved. The tables from which these data are derived are provided in Appendix B. They include the following: data on undergraduate and graduate enrollment and degrees reported annually in IPEDS College Opportunities On-Line by the National Center for Education Statistics; data on total and industry funded R&D expenditures drawn from *Academic Research and Development Expenditures* published annually by the National Science Foundation; data on patent and licensing activity drawn from *The AUTM Licensing Survey* conducted annually by the Association of University Technology Managers, Inc.; rankings of effectiveness of doctoral engineering programs in specific fields published in 1982 and 1993 by the National Research Council[9]; and rankings of the overall quality of doctoral engineering programs published annual by *U.S. News and World Report.* These latter rankings are viewed with considerable skepticism by many observers; however, interviews on many university campuses indicate that these ratings, no matter how problematic, often are followed quite closely by university administrators, because they believe that they matter in some way – clearly in terms of the quality of students applicants, but possibly also as a matter of institutional prestige. They are therefore included among the reputational ratings mentioned, but for reference purposes only.

[9] Although both of these rankings are very dated by now, they represent two time slices for the ERCs included in this study: a "before" and a "mid-point" during the Center's life as an ERC.

BRIGHAM YOUNG UNIVERSITY AND THE UNIVERSITY OF UTAH: ADVANCED COMBUSTION ENGINEEERING RESEARCH CENTER

Background and Overview

The Advanced Combustion Engineering Research Center (ACERC), established in 1986, is a two-university Center that involves the collaboration of Brigham Young University (BYU), a private, church-affiliated university, and the University of Utah (UU), a state-supported university.[10] The Center has been headquartered primarily at BYU, the home institution of the founding Director and, now, his successor. The state-run University of Utah (UU) in Salt Lake City was the second participant during the years of NSF funding. UU is a Research I university, while BYU describes itself as "a Ph.D.-granting institution with a strong focus on undergraduate education" and is Research II with no officially sanctioned objective to become a Research I institution. When the Center was established, ACERC represented about 20% of BYU's total external research budget (about $2M of $10M), while the share of ACERC funding going to UU represented about 1% of that University's total R&D.

ACERC established teleconferencing facilities between the two universities, and some of the Center-developed courses used these facilities. However, more of the ACERC's projects and Center-based courses were operated out of BYU, with UU students being transported to BYU for classroom sessions. Because of the concentration of activity and its importance to BYU, SRI's site visits concentrated on BYU, and this case study makes only occasional reference to the UU's participation in ACERC.

The cultures of the two universities are markedly different. BYU was founded in 1876 as a private, independent institution operated by the Church of Jesus Christ of Latter-day Saints (LDS). According to the Mission Statement of the University, its mission is "to assist individuals in their quest for perfection and eternal life," and the philosophy and culture of the University is heavily oriented around the religious and educational teachings of the Church's founding prophet, Brigham Young. Faculty and students are predominantly LDS members. UU is a secular public institution and LDS membership plays no role in its hiring or admissions policies and practices.

Compared with the other universities hosting the ERCs included in this study, BYU as an institution is, on the whole, less oriented toward engineering, with engineering degrees at the bachelor's and doctoral levels accounting for 5% and 8%, respectively, of total degrees conferred in 1999. In 1999, BYU had R&D expenditures of about $24M, double the University's $12M in total R&D throughout the previous decade. How much of this increase might be attributable to the ERC is unknown. Of the 1999 R&D total, industry was the source of about 12%, down from a high of 19% in 1987 but somewhat up in absolute terms. Of the departments most involved in ACERC (chemistry, chemical and mechanical engineering, and computer science), only its chemical engineering department was ranked – as 39.5 – in the NRC 1993 engineering doctoral program ratings. BYU's overall graduate engineering program is not rated by *U.S. News*.

[10] In the early years of ACERC, the University of North Dakota also participated, but dropped out when NSF funding did not reach anticipated levels.

BYU is also more heavily oriented to undergraduate education than any of the other universities associated with the ERCs included in this study, with undergraduate students accounting for over 90% of its 1999 total enrollment of about 33,000. BYU has a policy limiting graduate enrollment to 10%, although the percentage varies among departments and it was reported that there has been some relaxation of the ceiling. This was partly attributed to ACERC's role in enhancing the level and perception of the importance of research at BYU as part of the educational experience. Less explicit is a *de facto* ceiling on the amount of federal research funds that BYU would accept lest it be subject to too much government control.

The two participating universities initially had rather different research emphases. BYU was primarily focused on coal combustion modeling and process software: the Center's challenge in securing industrial support was to persuade its industry members of the utility of computational fluid dynamics for coal combustion. UU was originally involved in waste incineration, and this research program had more of a contract base. The research thrusts of the two institutions thus complemented one another, providing industry with a choice of which University to go to in seeking solutions for a particular problem.

In terms of outreach to minorities and women, both universities faced demographic barriers that made NSF goals frustrating and hard to achieve. Utah, in general, has a very small minority community on which to draw, largely concentrated in a Native American population. Although it draws from a national and international constituency, interviewees attributed this difference in part to the culture of the LDS Church, which stresses the role of women in the family as opposed to their professional careers. The percentage of women enrolled in engineering is considerably below the percentage of women enrolled at the University – approximately 10% compared to 50%. Most women who do enroll in engineering do so in computer science, which they seem to perceive as more compatible with combining family and a career. Attrition leaves the College of Engineering with about 5% women. Many participants, especially at BYU, felt that NSF was overly critical of the very limited success of their efforts at outreach in this environment.

Engineered Systems

ACERC participants reported a continuing lack of clarity about NSF's definition of a "systems approach." The initial proposal to establish an ERC asserted that the Center would take such an approach, and the founding Director, who was also Dean of Engineering, made frequent allusions to the need to do so. ACERC participants did believe that their general approach of trying to combine all of the fields and skills needed to attain some ultimate specific goal met the requirement. Initially, they were dealing with an industry that tended to use individual software modules to run various processes. Their objective was to provide industry with comprehensive models of large-scale combustion systems based on an experimental approach in which models of smaller components would come to be integrated into a larger "system." Center respondents reported that a "paradigm shift" in industry toward using the more comprehensive models as tools did occur, and took credit for having introduced this perspective. ACERC's reputation for computer modeling in part stems from its having played a lead role in assisting the combustion engineering industry in adopting comprehensive modeling as a design technique.

In addition to prescribing that the Center would fulfill the NSF-desired approach, the Director as Dean of Engineering was in a position to bring together faculty from various departments and influence project design to accomplish this. The current Director maintains that the Center continues to be vertically integrated to include fundamental research, experimental design, and test-bed applications. However, to some extent, whatever "systems" outlook existed is perceived to have diminished, which was attributed in part to the loss of infrastructure within ACERC with the end of NSF funding. There is also a sense among interviewees of losing some of the original central research mission. ACERC's broad placement of students in the energy industry has, however, enabled the Center to attract some industrial support that, combined with other new funding, supports some of the core research and sustains a systems approach. With the loss of professional staff who maintained the code as a result of the ending of ERC core funding, there is a sense that the faculty are now more involved in the research program, as well as with its applications. Meanwhile, students reported that their contacts with industry, with accompanying "hands-on" and team-oriented experience, represented a sense of a systems approach. Elsewhere in the University any development of an engineered systems approach seemed more the result of national trends in engineering education than attributable to the Center.

Strategic Planning

Strategic planning for engineering research and education at BYU is characterized by a combination of emphasis on bottom up initiatives by faculty coupled with an increasingly explicit determination by central administration that University support will be channeled to clusters of faculty in selected research areas. These positions combine BYU's long-standing emphasis on faculty initiatives with a realization that within the constraints on the quantity of funds to be made available to seed fund faculty research initiatives; it is not possible to support each individual. (As one administrator observed, in a department of 16 faculty it is not possible to fund 16 initiatives). The emphasis on clusters may in part be seen as a reflection of the University's favorable experiences with ACERC but also has independent causes. As noted by several faculty, much of what is happening in the direction of research at BYU – especially the thrust towards problem-focused research, the building of interdisciplinary teams, and the increased interaction with industry – is a natural, grassroots move towards maintaining active faculty research agendas in the context of the current competitive funding environment for academic research.

During most of the years of NSF funding, under the original Director, planning appears to have adhered largely to the original proposal's vision, as modified from time to time by NSF and internal reviews. The Center had a great deal of discretion in dealing with its NSF and industrial funding. However, the central administration did monitor carefully the Center's use of resources from the University, such as space and funding. Part of this was the desire to ensure that ACERC not become an independent research operation that, as noted above, diluted BYU's commitment to undergraduate education. Strategic planning did not really become an issue until near the end of the NSF funding when the torch was passed to a new Director. Now the Center is treated as a department within the College of Engineering and reports to the Dean of Engineering. The Director can therefore bring together other department heads in order to deal with problems or work on developing new projects. A major effort at conferring among current and potential faculty participants, as well with industry, has resulted in development of a new overall strategy for the Center's post-NSF development.

Interdisciplinarity

BYU was characterized by respondents as a very collegial place in which "ground up" initiatives are the rule. At least one faculty member who had experience with two Research I universities prior to coming to BYU was amazed at the amount of interaction that he found across departments and colleges in contrast to his previous affiliations. This in part was attributed to the commonality provided by the shared religious values of most of the faculty, but administrators characterized it as a general feature of the University's culture. Top down initiatives were the exception: while the Dean of Engineering took the lead in preparing the ERC proposal, of necessity there was broad faculty interest in and commitment to the initiative.

Despite the interactive culture, the explicitly interdisciplinary character of the Center was a first for BYU: prior to ACERC, the only significant interdisciplinary interaction reported at BYU took place between the mechanical engineering and chemical engineering departments through a combined laboratory. The expansion of team research from this limited base was said to be a startling transformation. At the peak of the Center's activity, there were seven or eight departments involved, including computer science and mathematics. Counting UU, as many as twelve departments were involved at one time or another. The degree of interdisciplinarity, however, was regarded as being largely determined by the nature of the research problems undertaken by Center thrusts – an example of the University's grassroots approach. Although BYU provided ACERC with renovated common space as a place where faculty could come together, the administration also wanted participating faculty to remain closely tied to their home departments. The Center's space did help make it more visible, however, which in turn attracted student interest.

The Center thus greatly enhanced the level of cooperative, interdisciplinary research taking place on the BYU campus. ACERC is said to have produced no paradigm shift, but rather to have been an important catalyst to foster faculty interaction and broaden it to more explicitly interdisciplinary projects. It altered few policies, but changed "practice" in the institution. ACERC has made the University more open to such centers: at least six were under consideration in 1998. Internally, however, support – especially in startup funding from the administration – is directed more at faculty development than at the interdisciplinary character of the center, and such centers must develop their own sources of support or University funds will ultimately be withdrawn. Moreover, most of the centers being contemplated will be quite small.

The Center's basic mode of operation was team-based projects, generally involving a mix of engineers, who are oriented toward controlled experiments, with scientists who provided the basic research underpinnings. In addition to attracting senior faculty to ACERC projects, NSF funds were used to start research programs for young faculty, who thereby developed an interdisciplinary approach to their research agenda.

Overall, faculty saw little resistance by administrators to the increased interdisciplinarity stimulated by ACERC. Indeed, University and college administrators were seen as encouraging interdepartmental initiatives in the competition for internal funding. It was common for graduate students to have committee members from multiple departments, and the practice was reported to be spreading to fields such as acoustics and optics. No faculty member who participated in ACERC was seen as in any way disadvantaged in promotion and tenure decisions by his participation in interdisciplinary research; indeed, most faculty saw those who participated in ACERC as being helped in their careers through the resources and opportunities to conduct research provided by ACERC. Faculty reported few visible changes in promotion and tenure policies, but noted that the need for faculty to document independent research was a recurrent issue. As was the case in a number of other universities hosting Centers, BYU's review process had to find ways of ensuring that the applicant's contribution to multi-authored publications was significant and not riding on the work of others.

Education

As noted above, ACERC's impact on education through its research program represents an extremely important impact on the institution's culture. BYU's emphasis on the primacy of undergraduate education meant that the Center engendered concern that its research focus would come at the expense of relationships with the students. This research component of the Center's activities was watched carefully by the central administration. Unlike UU, BYU's administration cared far less about the character of the research – be it basic or applied – than about anything that detracted from the education of students. There was also a concern that the large professional staff, much of it involved in developing software and maintaining industrial liaison, was rather removed from the students. ACERC was generally viewed as having avoided pitfalls in this area through careful cultivation of contacts with students at both the graduate and undergraduate level.

The character of the University meant that the Center probably directly influenced more undergraduate students than most. The relatively limited number of graduate students meant that ACERC always involved a substantial number of undergraduates working in the laboratory, who were encouraged to go on to graduate school. Undergraduate involvement in research, however, had been a pattern at BYU for decades: ACERC expanded such opportunities, but was not reported to have generated any major changes in culture or practice.

More of the NSF funding seems to have gone to students than at most ERCs. BYU policy is to fund all faculty lines directly, and not typically to seek support for positions from external research grants. The University limits the number of faculty FTEs who may be on released time in a given year to six, usually about two from the College of Engineering. Therefore, aside from the professional (i.e., non-faculty) staff, most of the NSF funds were used to support student participation in projects. With the end of NSF funding, there has been a drop in retention due to the loss of available support for students.

The Center provided a number of incentives for students to participate, ranging from scholarships to Center- and department-sponsored seminars. Students said that they particularly appreciated the opportunity to work on projects and have contact with faculty from more than one department. ACERC's REU program provided even more opportunities for undergraduates to become involved in the Center's research. The ERC's summer program helped attract some high-quality students to BYU graduate programs. However, there has been no effort to replace the loss of the REU funds, largely due to a lack of help or encouragement on the part of the central administration. In the future, the need to fund graduate students will probably reduce the participation of undergraduates from the approximately 50% that it was under the NSF funding.

The Center resulted in the modification of numerous courses. Content of existing courses was changed to bring in materials on combustion. New courses were developed at both the inter-departmental and inter-university level. Some courses were team taught, often with faculty from both universities. The modifications were reported to be perceived as resulting in very good courses.

Absent, as a factor affecting ACERC's impacts at BYU was distribution of indirect cost recovery funds. This stands in marked contrast to several other ERCs, where allocation of these funds was a defining aspect of the organizational and fiscal autonomy of an ERC, and of its relationships to colleges and departments. The reason that this did not affect ACERC stems from the organization and financial base of BYU. The University is a church-owned institution. The church provides core financial support for the University; in turn, the University turns over its indirect cost recovery funds to the church, where it becomes melded into the University's general revenues. In effect, as described by BYU administrators, the church's contribution takes the form of a subsidy to finance the difference between the University's expenditure budget, which is subject to church review and approval, and revenues from all other sources, including tuition, research grants, and indirect cost recovery. The BYU model was described as offering indirect cost recovery up-front in the form of direct infrastructure support (e.g. ACERC's space involved major outlays for renovation of the basement of an engineering building).

Probably the most significant impact of ACERC on the broader University was the fact that it raised expectations concerning the quality of research at BYU and its relationship to education. The Center contributed to a growing sense of the need to recruit quality graduate students. ACERC was seen as having demonstrated the importance of good graduate programs in enhancing undergraduate education. The Center represented a prized research focus and asset, and it was reported that the University's limited number of graduate programs have been increasingly successful in attracting good students. Rising qualifications were reported to characterize incoming undergraduates. More research-oriented faculty have been hired as a consequence. Broad placement of ACERC students has demonstrated their value to industry, and the external value of a BYU education is consequently viewed as having been elevated.

The enhanced role of research at BYU may, however, be producing tension with the University's traditional emphasis on undergraduate education. Changes are occurring: as mentioned previously, there was reported to be some relaxation of the nominal 10% limit on graduate enrollments. In addition, the new Dean of the College of Engineering indicated an interest in going so far as doubling its research base. It was noted, however, that such a program will require a very deliberate plan that balances limitations on the number and size of graduate programs, Board concerns about government funding, and efforts to build a broader industrial constituency.

Industry Interaction

ACERC's industrial constituency is the combustion-oriented sector of the energy industry, an industry with little tradition of investing in research. Many of the firms with which ACERC interacted were said to have voiced skepticism about some of the Center's research objectives, and ACERC had to demonstrate the applicability of computational fluid dynamics to industry's concerns. However, the lack of an industrial research base meant that the ability to leverage the NSF funds represented a major attraction to their prospective members.

Before ACERC, limited contacts between industry and the University existed. Faculty perceptions were that the Center definitely did improve ties to industry, and these ties provided some faculty with windows on interdisciplinary research that they would not otherwise have had. A student who had returned from industry for an advanced degree found an entirely new mode of interaction. Before ACERC, industrial support took the form of a single firm contracting with a faculty member for a relatively narrowly defined topic of immediate relevance to the firm. With the Center came a broadening of the research questions submitted by the aggregation of firms affiliating with the center – a "big picture view." Interest in working with industry was reported to have spread to other departments, such as physics, a shift in culture toward more applied work.

The Center limited its membership to U.S. companies as a consequence of its perception of the relationship of the ERC program to U.S. competitiveness. Offices for industrial representatives were made available in the Center's facility, which made it more convenient for them to spend a week or more on campus to observe simulations as well as learn the software. At the peak of its operations under NSF ERC funding, ACERC had 43 members.

The Center sees its impact in terms of technology transfer as occurring in two main areas. First is in the placement of students in industry, a process that started slowly but now represents a situation in which there are Center graduates in most companies in the industry. The development of a cadre of well-placed alumni helps ACERC to develop industrial contacts and to convince companies of the value of supporting ACERC's core research agenda. The second is in the sale or licensing of software to industry, which has ranged from providing special modules to insert in a company's own set of programs to the development of complete codes for a particular company.

BYU is only modestly involved in state-wide development efforts. Overall, BYU places little emphasis on playing a role in local economic development. The University's international constituency and spiritual underpinnings provide no basis for this. In fact, it has policies that deter technology transfer through the production of spin-off companies: faculty who want to generate a spin-off company must either keep an arms-length relationship with the University or take leave until they are comfortable with turning over management of the company to others. UU, by contrast, actively encourages such spin-offs.

Intellectual property rights (IPR) has become an important facet of technology transfer at BYU and provides a significant stream of revenues. The University has developed what administrators view as an excellent Technology Transfer Office. Although ACERC's operations raised some issues related to technology transfer, the Center and the Office basically developed at about the same time. Little direct influence of ACERC upon the Office's policies or operations was reported; however, the University is among the top 25 in revenues derived from inventions–about $3.1M in 1998. Faculty receive 45% of this, the rest being split half each to the colleges and the central administration. Although the faculty can take the money as income, the option of obtaining matching funds for a research project leads to a large proportion being reinvested in the University. BYU administrators and faculty frequently point to WordPerfect as the big fish that got away before they had established the Technology Transfer Office, and that missed opportunity was a primary motivation for the Office's establishment.

Despite the importance of this stream of revenue to the University, the Office largely let the Center define its own role given the special circumstances of its relationship with its industry members. Revenue became an issue for a different reason. Although ACERC perceived its primary role to be technology transfer rather than revenue, the centrality of software as its main output made this difficult. Companies demanded support in order to adopt ACERC software, which the Center could not provide without additional funding. It was therefore necessary to work out ways of meshing membership fees, which granted fairly open access to Center products, with licensing policies that covered support requirements. Ultimately, it was conflict over IPR policies that led to the departure of one software-oriented faculty member for UU.

Overall Impacts

ACERC's research orientation is probably the primary source if its influence on BYU's culture. The University has not formally changed its outlook concerning ceilings on the number graduate students and government funding. However, it has hired more research-oriented faculty in an effort to upgrade departments; research has become a more integral part of the educational process; and there are ambitions, especially in the College of Engineering, for an increased research budget that will need to be harmonized with the University's traditional position on these issues. While valuing the ERC for its contributions to the campus, concern was expressed by research administrators and deans, as well as by many faculty, that research activities not overshadow the core commitment to teaching undergraduates. Thus, the ERC has established a tension between the University's powerful undergraduate education culture, strongly supported by its board and most of its administrative agents, and increasingly research-ambitious faculty and College administrators, many of whom see research and graduate programs as essential to a continuing improvement of BYU's undergraduate programs. It remains to be seen how BYU will deal with the overall enhancement of research on campus in the context of the University's emphasis on undergraduate education.

While BYU is the focus of this case study, the importance of the Center to UU should not be underestimated. Some at BYU believed that it had better assimilated and put the Center experience to better use than BYU. In the post-NSF funding era, the two universities have taken different paths. UU, freely acknowledging that it acquired essential skills through the ACERC experience, successfully competed for a major award from DOE. It has adopted the Center for the Study of Accidental Fires and Explosions (C-SAFE) name for the new interdisciplinary operation and has not retained the ACERC name, which BYU continues to sustain. However, UU expects to continue working with BYU faculty, and ACERC is listed as a collaborator on C-SAFE's web page. Despite the fact that more funding now flows through UU, collaboration was reported to have held up at roughly a 50-50 ratio of faculty in 1998.

CARNEGIE MELLON UNIVERSITY: DATA STORAGE SYSTEMS CENTER

Background and Overview

Carnegie Mellon University (CMU) is a private, independent liberal arts and professional institution established in 1967 through the merger of the Carnegie Institute of Technology (founded in 1900) and the Mellon Institute (founded in 1913). CMU's primary institutional strengths are considered to lie in science, engineering, and drama. Undergraduate enrollment for the 1999-2000 academic year was just over 5,000, while graduate enrollment was just over 3,000, making the University one of the smallest (next to Lehigh) of those hosting the ERCs included in this study. The Engineering School, known as the Carnegie Institute of Technology (CIT), accounted for 26% of the bachelor's degrees and 42% of the doctorates awarded by the University in 1999, making CMU second only to MIT among this study set of universities in its strong orientation toward engineering. Industry funding accounted for about 13% of CMU's total 1999 R&D expenditures of about $142M, ranking it 67th among all U.S. colleges and universities in terms of total R&D, but 26th in terms of industrial support. This latter ranking was down considerably from CMU's rank of 6th in the early years of the two ERCs on campus, when funds from industry accounted for closer to 20% of the University's total R&D: in absolute terms, funds from industry at CMU had remained relatively static over the 1987-1999 period, while other universities had gained in comparison.

The NRC's 1993 effectiveness ratings rank CMU's chemical, electrical, materials science, and mechanical engineering departments (those most closely aligned with the Data Storage Systems Center) at 12th, 8th, 9th and 19th, respectively – all slightly up from the 1982 ratings in those cases for which they are available. *U.S. News* ranks CMU's graduate engineering school 8th among all U.S. universities, rated in 1999 behind only MIT and the University of Illinois among universities included in this study.

Carnegie Mellon is the home of two of the ERCs included in this study: the Engineering Design Research Center (EDRC) established in 1986 and the Data Storage Systems Center (DSSC) established in 1990. With two of the earlier ERCs on campus, Carnegie Mellon is the university that had received the most support from the ERC Program (22 years of direct support for the two ERCs combined) of the universities included in this study. Of the two ERCs at CMU, the DSSC is the Center included in the set of ERCs selected for site-visits under this study, and is the primary focus of the discussion that follows. It should be noted, however, in addressing the impacts of the ERC that may have spread beyond the immediate faculty, students, and departments directly involved, the extent to which such impacts are attributable to the influence of DSSC as opposed to EDRC or the combined effect of the two ERCs is difficult to ascertain.

The DSSC grew out of an earlier Magnetics Technology Center (MTC) that was established in 1983 based on funding primarily from IBM and the 3M Corporation. By 1990, when the MTC became an ERC, it had grown to about a $5M/year operation, almost entirely supported by companies (although it had Department of Defense and Department of Energy funding as well). While the MTC was viewed as a successful example of an industrially funded university research center, faculty were concerned about their inability to develop a long-term systems-oriented research program, because of the diverse needs and expectations of the individual company members regarding what projects should be pursued. As a result, a proposal was submitted to NSF to form an ERC to focus on long-term research and education in the field of data storage systems, with particular emphasis on developing systems applicable for use in computers. The systems orientation was therefore one of the chief motivating factors in the formation of the DSSC and has remained an important organizing principle in its research and educational activities throughout its existence as an ERC.

An emphasis on interdisciplinarity and industry collaboration is widely held by CMU faculty and administrators to permeate the University culture. Cross-departmental research and industrial support are prevalent in the Colleges of Science and Engineering, due in large part to the University's strategic plan, which has embraced these modes of research for close to twenty years. Within this culture, the DSSC is seen as a leader in industrial collaboration and interdisciplinary research. A number of interviewees believe that DSSC is the most successful center on campus, especially in terms of working with industry. Many faculty and administrators see DSSC as a model of a successful research center, and come to it for advice when they prepare proposals for similar interdisciplinary or center-based research efforts. The University administration recognizes the Center as one of the University's top research units and as a leading national player in the field of data storage, among universities and industry alike. The DSSC has attracted support from major corporations such as IBM, Intel, and Kodak. In 1998, it had close to 80 industrial partners. DSSC’s activities have been widely credited as contributing to Seagate's decision to locate a $30 million research center in Pittsburgh.

Although Carnegie Mellon had a strong atmosphere of cross-departmental collaboration and industry interaction well before the DSSC, the University administration views the ERC objectives as validating CMU’s research culture. DSSC both enhanced the magnitude of interdisciplinary activities among the academic units involved in its programs and reinforced this orientation across the University. Its extensive interactions with industry, including a new ability to integrate longer-term fundamental research with shorter-term applied problems of immediate interest to industrial sponsors, also introduced new possibilities for other academic units in their relationships with industrial sponsors. Faculty report being excited about their involvement with the Center because it gives them fresh concepts to think about that they would never have seen if isolated within their home departments. DSSC is considered an asset by many departments in their recruiting efforts, as prospective students see the opportunity to develop expertise in the Center's burgeoning field. The prominence of the Center is said also to be a major force in strengthening the College of Engineering’s ranking in *U.S. News*.

The DSSC is seen as a major catalyst in the revamping of the Department of Electrical and Computer Engineering’s (ECE) undergraduate curriculum. In turn, that curricular change was adopted throughout the College of Engineering and even, by some accounts, by other universities. The ECE department recently won an award for its curriculum from the Institute of Electrical and Electronics Engineers (IEEE), and credit was given in large part to the persuasiveness of DSSC’s interdisciplinary nature throughout the ECE department.

Engineered Systems

The ERC funding reportedly allowed faculty in the DSSC to develop systems-level goals and to use these goals to motivate and select its research projects. Engineering test-beds are reportedly required in each of the Center's thrust areas in order to integrate and quantify their systems-level advances. The optical recording research performed at the DSSC was considered novel at its inception. Industry was said to have quickly benefited from the invention of high quality devices that were readily adopted from the research stage to production. The rapidity of the development stage in this research is seen as testimony to the extent to which the systems focus is embedded in DSSC research.

From the perspective of several interviewees, the systems focus of the DSSC contributed to its having a larger impact on CMU than did the earlier MTC. It allowed the Center to change its research from incremental improvements to one of reinventing an entire technological system. This orientation, in turn, meant leapfrogging incremental improvements in separate components. It was thought that companies could not attempt this type of research. The systems approach thus permitted the DSSC to combine long-term fundamental research with specific R&D applications of high saliency for industrial sponsors. DSSC is now being approached by industry for more typical short-term industrial research projects in this area, which is attributed largely to its earlier research accomplishments at a more fundamental level.

The spread of a systems orientation outside of DSSC to other academic units, however, is less evident. One faculty member associated with the Center reported that he is constantly preaching the need for a systems approach to other faculty in his home department, which would seem to indicate that the systems focus may not be all that prevalent throughout the University.

Strategic Planning

ERC Program support is held to have made a modest difference in the way the Center went about strategic planning, but again these differences were considered incremental changes from prior practices. The Center Director always espoused strategic planning as a guiding Center precept. After the ERC award, however, the strategic planning became more formalized, the Center's sponsors were involved more in the process.

The University itself has a top-down strategic plan and an advisory board to oversee the implementation of the plan within each department. This strategic plan encompasses a vision of CMU as a leader through its traditions of innovation, problem solving, and interdisciplinary collaboration. The University, however, has relied on strategic planning long before the advent of an ERC on the campus.

Interdisciplinarity

Carnegie Mellon University was widely described by interviewees as having a strong tradition of interdisciplinary research and education. This orientation comes from a long-standing strategic recognition that the University is too small to be able to achieve academic excellence in the mainstream academic disciplines, e.g., chemistry and physics. It therefore has purposively sought out niche areas located at the intersections and interstices of research and education. The interdisciplinary orientation is reinforced by its tradition of close ties to industry; industrial R&D programs are inherently of an interdisciplinary rather than disciplinary character. Finally, CMU was described as having a relatively flat organization structure, with few hierarchical administrative barriers to cross-unit activity.

Cross-departmental and cross-institutional relationships with other universities are considered part of the tradition and culture at Carnegie Mellon. Interviewees stressed that one of the reasons people are attracted to CMU is that they want to work with other people. Joint departmental appointments were said to have been in place at CMU long before they were instituted in other universities. Potential new hires are generally interviewed by more than one department. The promotion system is broad and flexible enough to accommodate collaborative efforts. Faculty are said to actually be encouraged to seek opportunities outside of their departments.

Many of the ERC Program objectives for Centers were already being met by the MTC before it became an ERC. For example, faculty from a number of different departments were involved in the Center, industry interaction was extensive, and strategic planning was ingrained in the Center's operational modes. Once the Center was established as an ERC, however, it did even more of these things. The differences were said not to be radical, but incremental. DSSC's level of funding as an ERC exceeded the resources available to MTC. Thus DSSC was able to bring in faculty from even more departments. Research could be conducted that the industrial sponsors did not necessarily care about. Earlier, companies associated with the Center had emphasized their interest in having CMU focus on short-term, applied R&D projects, and did not particularly have an interest in the longer-term research of interest to faculty. DSSC, incorporating NSF's emphasis on the importance of the long-term research underlying the applications of the future, was able over time to convince firms that it was to their interest to support this orientation of the ERC. The NSF funding also enabled researchers associated with the Center to work on understanding more fundamental problems, whether the industrial sponsors had an interest in them or not. For example, work was initiated on optical recording technology, which broadened the Center's portfolio and was considered important to the long-term needs of the country.

One of the University's early successes in interdisciplinary research was said to be its Robotics Institute. The Robotics Institute, which brought together the computer science, electrical and computer engineering, and mechanical engineering departments, was formed in the late 1970s. In the 1960s, the University made an early move to invest heavily in the computer science and computer engineering departments. This investment is seen as having paid off profitably, both in terms of national recognition and reputation, as well as in major external research awards. A high wall between computer engineers and computer scientists was generally held to exist both in industry and academe; the Robotics Institute lies at the interface of these disciplines. The Institute conducts high-profile research projects for NASA and industry, and although it formally resides within the College of Computer Science, the Institute offers an M.S. and Ph.D. in Robotics, more commonly found in Colleges of Engineering.

The DSSC's research is seen as being at the forefront of the state of the art in each of its collaborating departments. The physics department contributes knowledge of magnetics and magnetic fields beyond what an electrical engineer might know, and a similar situation exists with respect to the involvement of other departments. DSSC faculty from science departments indicated they are happy for their students to see the systems emphasis at the DSSC, as they would not see it in their home departments. Collaborating engineering faculty also say they preach the systems approach in their home departments. Some faculty reported that working with faculty from other departments keeps an engineer honest. When working within a department, it is easy to optimize selected qualities but to ignore qualities that are incompatible with an overall system. An anecdotal example of this problem was presented as “obtaining a signal, but ignoring the noise.” Working on interdisciplinary projects was said to increase the emphasis on the overall picture, thus keeping engineers from this tendency.

The DSSC's role in interdepartmental and department-Center relations is generally considered positive. Faculty use the Center's prominence as a marketing device for external funding. No departments discourage their faculty from working with the Center. However, some departments worry about losing students to the DSSC because they can become heavily involved in the Center's research, and was said to have occurred a few times. The Center sometimes buys the teaching portion of a professor’s annual assignments from his or her department: this reportedly sometimes creates headaches for the departments because they must then find a suitable replacement for teaching classes, and the students at CMU are said to be quite vocal when teaching is unsatisfactory. The Electrical and Computer Engineering department itself worries about the DSSC becoming too pervasive; the chair would like to have more faculty involved in research outside of the Center.

Carnegie Mellon's policies regarding operating budgets and indirect cost recovery (ICR) are designed to facilitate cross-departmental collaboration through centers such as the DSSC. First, the Director of the DSSC reports to the Dean of Engineering, as he would if the Center were a department. However, unlike departments, no faculty member is ever appointed to a center; they are all associated with a department. This is true even of the research faculty, who are entirely dependent on “soft money” from grants and contracts. Second, CMU does not provide general operating funds to support centers; instead, centers are dependent totally on the external funding they are able to generate. Third, as a matter of university policy, ICR is never shared with colleges, departments, or centers. The University views the ICR as its real costs. The point of this budgeting system is to facilitate research centers as intersections of collaboration by keeping them out of competition with departments. One way through which the University helps out centers, however, is by not charging overhead on industry membership fees. In addition, centers sometimes receive some support from discretionary funds from the Provost's office.

Education

DSSC was seen to have had an important educational impact via its influence on major curricular changes within the electrical and computer engineering department (ECE), which eventually spread to the whole College of Engineering and is said to be gaining attention at other universities. At the time of the inception of the DSSC, ECE was looking at ways to maintain breadth and scope of the electrical and computer engineering undergraduate curricula, while maintaining the program's length at four years. The Department consolidated the computer engineering and electrical engineering majors into one major, imposed a minimum of core requirements on undergraduates, and allowed them to pick and choose any courses after that. Faculty in turn created courses based on their interests, and thus undergraduates were exposed to interdisciplinary topics to an unprecedented extent. Undergraduates could choose to pursue an area within electrical engineering with guidance from his or her advisor. As noted previously, the IEEE recently presented an award to the ECE department for its curricular model.

The NSF/ERC funding is reportedly directly responsible for the involvement of undergraduates in research. Before CMU received ERC funding, relatively few undergraduates were involved with the predecessor MTC. Under the ERC, however, undergraduates get direct research experience through a laboratory course, which has led to a number of undergraduates publishing articles. The Center created a summer program that involves the English Department helping undergraduates associated with the Center polish their oral and written communication skills.

The ERC Program support was not thought to have made much of a difference in the way the Center interacted with students at the graduate level. However, it was credited with helping Center faculty do a better job of educating undergraduates. About forty or fifty undergraduates are now associated with the Center, many more than was the case in its pre-ERC status. The Center now has an REU program for undergraduates from other universities, which it did not have prior to its ERC status. The ERC funding also enabled the Center to develop more outreach programs to other universities; it had been doing this previously, but now was able to do it in a more concerted fashion.

Also at the graduate level, the Center is considered valuable to the departments for educational and recruitment purposes. Departments report that prospective students are excited to see that there will be an opportunity for them to develop expertise in the growing data storage field. Students were said to find intellectual excitement through association with the Center. For example, faculty from outside their departments can serve as Ph.D. thesis advisors, and almost every Ph.D. committee has a member from industry. Industry representatives reportedly like to sit on such committees, as it keeps them plugged in to the kind of research the students are undertaking. It also helps them in recruiting the best students. Firms reported that students hired from the DSSC did not require the 12 -18-month acclimation period that new hires normally need, but instead were said to “hit the ground running.”

In all, close to 10 new courses were created by the Center and about 50 components having to do with data storage were introduced into existing courses. In addition, a CMU faculty member wrote a textbook on Fluid Mechanics that is based heavily on work performed in the DSSC. The faculty member cannot see how this would have happened without the DSSC.

Industry Interaction

Although collaboration with industry has long been the norm at CMU, the DSSC is nevertheless seen as a model for the rest of the University in this regard. The University administration routes many inquiries from other departments regarding methods for interacting with industry to the DSSC. The Center's long-term survival plans after ERC base funding ceases revolves around obtaining its support solely from industry, a model very unlike what is typically seen in ERCs about to "graduate." DSSC is supported by some 80 different companies, 60% of these including major international firms such as IBM, Microsoft, Kodak, Seagate, and Intel.

The Center maintains an industrial advisory board that meets semi-annually to discuss strategic plans, research aims, membership guidelines, and long-term support for the ERC's research. The Center is also part of the National Storage Industry Consortium (NSIC), a joint venture of 30 industries and 19 universities, which the Center and its long-time Director had a large hand in starting. The goal of the NSIC is to promote and support research in information storage technologies through technology transfer. The Center collaborates on 5 research projects totaling just under $100 million through the NSIC.

Industry representatives were said to be fairly highly visible in the Center, often using the Center's test-beds for making measurements for specific projects. The opportunities for interaction with industry available to students associated with the Center were considered a real plus by both students and faculty. The number of students placed in industry as a result of this interaction was thought to be one of the key impacts of the center.

The Provost believes that the DSSC is ultimately going to be good for the Pittsburgh economy because of its strong national industrial connections. The Center is helping to make Pittsburgh a magnet for other companies. Seagate, for example, announced that it will make Pittsburgh the home for a new $30 million research center, specifically because that is where the DSSC Director wanted it, according to an Associated Press report.[11] Industry was thought to be putting a lot of money into the Center largely because of the way it shares intellectual property. The Center's policy of allowing royalty-free licenses for its patented technologies for industrial firms that pay the Center's premium membership fee is considered one of the things that attracts industry to the Center.

DSSC's policies on intellectual property rights do differ, however, from those developed by CMU, and the differences have become a source of disagreement between the Center and CMU's central administration, as well as faculty. CMU's general policy is that it owns all intellectual property generated by University faculty and researchers. The faculty, as inventors, receive 50% of any licensing fees derived from patents.

The Center, however, under an arrangement grandfathered by its forerunner, the MTC, prior to the University's having in place its own IPR policy, provides royalty-free licenses to all of its Associate Members who subscribe at the highest fee level ($250,000 per year). This includes *all* DSSC patents, whether generated by DSRC faculty, students, or other faculty who simply use the Center's facilities. In addition, industry-sponsored projects at the Center always include royalty-free access to any results of the research. The faculty and the University lose income as a result of this policy. The Center sees this as the correct policy for Center research because the Associate-level members are the leaders of the industry; they dominate the design

[11] *Centre Daily Times*, August 26, 1998.

that are used, and other companies will have to follow their lead. Thus, while the leaders of the industry are given non-exclusive royalty-free licenses, other companies in the industry would ultimately be forced to pay license fees for the use of these patents.

The Center's IPR policies have become an issue in the University as faculty have become much more prone to patent. The University is now trying to define faculty rights compared to company rights. A faculty member has to give up some of the normal University rights to IPR to be a part of the DSSC, where the model is for shared research results. This was considered an issue that the University is going to have to address in the future.

The Technology Transfer Office confirmed that the relationship with the DSSC has its own rules, which complicates the Office's operations. The intellectual property policy of the DSSC was being tested for the first time at the time of the SRI interviews. The Technology Transfer Office acknowledged that they receive about ten disclosures a year from the DSSC, and that the office was at the time working through the first DSSC patent in which a large number of member and non-member firms had a great interest; so this could raise some additional challenges. The DSSC's concern is that it not alienate any clients. Companies have common technical problems, but each from their own particular slant, so the companies do not really mind sharing the patents. However, with the DSSC's policy, the inventors get nothing for their patents. The DSSC's view is that, by contrast, they *are* getting DSSC research support or the use of its facilities. Nevertheless, the investigator versus the companies has become an important issue on campus.

While the Center's impact on CMU's traditional, generally supportive culture of working with industry was relatively minimal; it does appear to have had important impacts on how member firms perceived their relationship with the University. As noted previously, companies were said to have begun to appreciate the fundamental research efforts of the Center as part of the longer-term systems perspective. In addition, the Center was said to have had major impacts on the competitiveness of the data storage industry. Several interviewees commented that it is quite likely that the industry itself would be different were it not for the Center, its research operations, the education it provides its students, and the interaction it enables among companies in the industry itself both in the Center and through the NSIC consortium it helped to found. In the Provost's view, this has put CMU at the forefront of data storage technology among its peers, as well as among companies themselves.

Overall Impacts

As an institution, Carnegie Mellon University embodies many of the characteristics the ERC Program was designed to encourage long before an ERC – either DSSC or the earlier EDRC – was established on campus. The culture of interdisciplinarity at CMU dates back to the 1070s, when the University, given its relatively small size, decided to forgo competition with more prominent institution on a discipline by discipline and instead find a niche in research that crosses disciplinary lines. Interaction with industry has also long been encouraged at CMU. Undergraduate involvement in research, though not heavily emphasized throughout the University, is by no means uncommon.

In terms of discrete impacts related to the ERC Program's objectives, emphasis was placed on degree rather than kind. Although most ERC-like characteristics are common at CMU, they are more intense and more formal in the Center than elsewhere in the University. Although most ERC-like characteristics are common at CMU, they are considered more intense and more formalized within the DSSC than elsewhere on the campus. The DSSC was said to have provided validation of the University's strategic approach. DSSC serves as a model for others on campus of how to work with industry, how to involve undergraduates in the research process, how to structure an interdisciplinary team approach and how to work effectively with industry. Thus, the impacts of this ERC on the broader university in which it is based are primarily incremental changes that reinforced and served to showcase many of the features for which the University is well known.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY: BIOPROCESSING ENGINEERING RESEARCH CENTER

Background and Overview

The Massachusetts Institute of Technology (MIT) was founded in 1861 as a private University and technical institution. With a total undergraduate and graduate enrollment of just under 10,000 students, MIT is the third smallest (next to Lehigh and Carnegie Mellon) of the 16 universities that house the 17 ERCs considered in this study. Like Lehigh and Carnegie Mellon, MIT is heavily dominated by engineering at the graduate level, with Ph.D.s conferred in engineering accounting for close to half of the 1999 total. MIT's enrollment is almost equally dominated by engineering majors at the undergraduate level, where they account for 42% of bachelors degrees conferred in 1999.

MIT is among the preeminent engineering educational institutions in the United States, consistently ranking among the highest in National Research Council effectiveness ratings of graduate engineering programs, as well as in far more problematic ratings produced annually by *U.S. News*. MIT is described as a university of very strong departments. According to the Provost, 17 of MIT's 22 departments rank in the NRC ratings among the top 3 in their respective fields; the University "has peaks and no valleys." No other university has such a record. The uniformly high quality of departments was said to create respect across units, facilitating a strong tradition of interdepartmental research that has existed for at least 60 years.

MIT is heavily research oriented. Despite its relatively small size, it has in most years ranked among the top five universities in the country in terms of total R&D expenditures, at about $400M annually. Roughly 15% of MIT's total R&D is funded by industry, consistently ranking for much of the 1980s and 1990s as the highest of any U.S. university in terms of absolute dollars from this source until 1998 and 1999, when it was surpassed by Duke University, another of the institutions associated with an ERC included in this study.

The Bioprocessing Engineering Research Center (BPEC) was one of six Centers established among the first cohort of ERCs in 1985. In 1995, the Center successfully recompeted for a full, additional eleven years of ERC Program support (subject to successful periodic NSF reviews) – the only original Center to do so (a few others had obtained one to three years of additional program support). In 1996, MIT was awarded a second ERC, the Center for Innovation in Product Development. With two ERCs representing a combined 19 or so years of ERC program support on the campus to date, MIT ranks with Carnegie Mellon (2 ERCs representing a combined 22 years of Program support) as the highest direct investments of the NSF ERC Program in a single institution.

MIT has a long history of interdepartmental research organized about centers and laboratories. An estimated 61 interdisciplinary laboratories, centers and programs were in operation in 1998, while an estimated 46 were in existence in 1985 when BPEC was founded.

Within such a context of an institutional culture close to the ERC Program's philosophy, BPEC was seen as very much within the MIT tradition. Even so, BPEC is held by administrators and faculty alike as having had significant intellectual and organizational impacts on the University. While many of the centers and laboratories at MIT were said to be interdisciplinary, BPEC was considered unique in the degree of its cross-college collaborations.

The most direct impact of BPEC was the creation of new links between the department of chemical engineering in the School of Engineering and the department of biology in the School of Sciences. BPEC is seen as having come along at a time when the historical division of disciplines was retarding advances in biotechnology research. For about 10 years prior to the establishment of BPEC, MIT had a number of multidisciplinary applied biology programs, supported by various grants from the NSF and other Federal agencies that involved collaboration among faculty in engineering, biology, and chemistry. Still, as of the early 1980s, even with these initiatives, only a small number of faculty in chemical engineering were interested in biochemical engineering, and their interests were directed more to process engineering than to biomolecular research. Early discussions between these faculty and those in biology revealed major gulfs. The two sets of faculty believed that they did not speak the same language; biology faculty were seen as finding the research problems of chemical engineering faculty uninteresting. Moreover, unlike many institutions, the lure of additional funding for research from participation in an ERC was said to have had limited impact on MIT faculty, many of whom had individual research programs equal to or larger than that provided by an ERC. The BPEC Director found that the only way to attract the kind of faculty he wanted to the ERC was through its intellectual challenges. He emphasized that the chief incentive for working in BPEC was the excitement of working with other faculty, students, and firms; it was not the ERC funding *per se*.

By the late 1980s, a major transformation in relationships between the participating faculty had occurred, caused in large part by the research and educational activities of BPEC, as well as by the complementary research interests, trust, and communication that had developed. Interaction among faculty in BPEC also led to a change in BPEC's research agenda. It began to shift from bioprocessing to research questions of greater interest to biologists. Chemical engineering faculty began using molecular biology research as the core of their own research. This shift in emphasis, in turn, attracted even more biologists to the Center. Although most interviewees emphasized the two-way exchange between chemical engineering and biology, one observed that while the Center brought biology into engineering, it had not brought much engineering into biology. BPEC did not change the way biologists did research, although it did show them what engineers could do.

The new collaboration among faculty forged by the ERC is seen as having spawned a new discipline, in which cell and molecular biology are at the core and engineering represents the translation device. These links are viewed as catalysts in the pending creation by MIT of a new intercollege unit, a Division of Bioengineering and Environmental Health (BEH), which will involve biology and six of the eight departments in the School of Engineering. Establishment of BEH is seen by administrators and faculty as "incredibly significant." BEH will formalize on the education side the research activities initiated by BPEC. The last time MIT was reputed to have formed a new academic unit was in 1953.

MIT administrators and faculty frequently state that the mission of their University is to "lead" in the development of new research and educational fields. BPEC and the pending new division are seen as essential new organizational arrangements for MIT's strong departments in biology and chemical engineering to remain ahead in the pending transitions in their fields.

Engineered Systems

Different perspectives were offered about BPEC's impact on an engineered systems approach. Some respondents described the term as an NSF flag to salute, but otherwise vague and having little descriptive content. Others described BPEC as embodying a systems orientation, although their definition of the terms varied.

In its broadest usage, BPEC was held to represent a systems orientation because its research projects went from biological properties to pharmaceuticals to delivery. Another definition was that BPEC embodied a systems approach because its research addressed problems that were fundamental from both theoretical and applied perspectives. However, in general, given the relatively strong "science-orientation" of BPEC compared with most ERCs, BPEC was thought to be less systems oriented than others.

Strategic Planning

Strategic planning within BPEC was said to have resulted in a change in research thrusts over time, representing a constant effort to be at the frontiers of science. Some BPEC faculty reported that they were recruited because the center realized it needed to conduct research on topics that were proving to be a bottleneck in other aspects of its research. Nevertheless, the Director admits to several mistakes in BPEC's strategies over the Center's life, and to several critical reviews by NSF site visit teams in its past proposals for renewal. At the time of the SRI site visit, the original Center Director was planning to step down and a new Director had been identified. BPEC was in the process of identifying new research thrusts, in part based on the recruitment of four new faculty to become involved in the Center. As part of the process of developing a new "vision," an *ad hoc* scientific advisory board comprised of MIT faculty and industrial representatives was convened to determine where industry R&D was ahead of BPEC's work and where BPEC was making a valuable research contribution, and to revise its strategic plan accordingly. The Center Director considered the involvement of that committee, with the series of iterations of writing, rewriting, etc., very important in getting the new vision established, which in turn would influence the ability of the Center to get approval from NSF for continued funding for the next five years.

One reported result of the strategic planning in the Center was a constant turnover in the faculty. Center management felt a need to keep the reins tightly focused on the plan, so as to be fully responsive to the industrial advisory board and the NSF site visitors. One fallout of strategic planning was to complicate faculty plans for and commitments to graduate students. Faculty involved in BPEC frequently used the research support they received from the Center to support graduate students. It is therefore important that they learn as early as possible when their research will no longer be supported by the Center, so that they can find other support for their students. As most faculty were said to have multiple sources of funding available, generally at significantly higher levels than what is provided by the Center itself, the problem was not considered major.

Interdisciplinarity

Few barriers are held to exist to interdisciplinary research at MIT. Research at MIT is heavily organized about centers and special laboratories. (For example, of the 105 faculty in electrical engineering and computer science, 100 are engaged in research in such units). This organizational arrangement was not regarded as harmful to departments; rather, departments are viewed as feeders of faculty into laboratories. Deans noted that they couldn't care less about which faculty were working with which laboratory. Cultural differences in faculty proclivities to working outside their own laboratories were noted, however. In chemistry, few if any faculty conduct their research outside the laboratories within their departments. In biology, 50% of the faculty research is conducted within the department, 50% in the Whitehead Institute.

Despite this orientation toward interdisciplinarity, it was noted that junior faculty still needed to be careful where and how they publish, because the decision affected their personal professional growth. If the research was conducted as part of a team, or if there is more than one author on a paper, it was considered important that the other authors be already well established. Junior faculty had to establish their own identify and where they are going. Participation in the Center itself was said to be neither an asset nor a detraction in terms of tenure and promotion. However, it was also reported that most of the faculty associated with the Center are tenured.

The creation of BEH is seen by administrators and faculty as raising MIT's commitment to interdisciplinary research, particularly between departments in the Schools of Science and Engineering, to new heights. The Division will have the authority to hire and promote faculty, as well as to grant tenure. The University's philosophy is that it needs to develop the new organizational structures that are often required in fields that are new. (MIT is also considering a divisional structure for its new initiatives in neuroscience.) BEH will be comprised of faculty with three types of status: those who are assigned entirely to the new division; those who are assigned half to the division and half to their home departments; and those who are assigned entirely to their home departments but take part in some of the division's activities. This will not be just a listing for advertising purposes. Faculty who are at all listed in a department or division have to actually teach classes in that unit. This new organizational structure will give the University the ability to hire and promote truly interdisciplinary faculty, who might not fare so well in departments, which tend to stay within stringently defined disciplinary boundaries. BPEC was said to have had a "profound" influence on making BEH happen. The administration observed the role that biology was having on chemical engineering research within BPEC and felt a need to formalize biology within the overall engineering curriculum, not just chemical engineering. It was thought that many of the engineering career opportunities of the future will involve links with biology. BPEC is also credited with providing the impetus behind the creation of a new laboratory in the Mechanical Engineering Department to focus on bio-instrumentation systems.

Several respondents noted that interdisciplinarity was necessary to maintain the University's intellectual leadership. The vision of researchers engaged in theoretical bioscience cannot be fulfilled without an appreciation of instrumentation and a receptivity to analytical skills and techniques developed in engineering disciplines. The biological sciences are being radically transformed by developments in instrumentation and data processing. Researchers need to be able to process large quantities of data differently than they have been accustomed to. From the perspective of engineering, faculty in their research and students in training for careers either within and without academe were held to need a better understanding of the science that underlies existing and latent engineering problems.

BPEC involves faculty primarily from the chemical engineering and biology departments, but also has faculty participants from the departments of chemistry and brain and cognitive sciences. While BPEC is credited with forging new levels of interaction between faculty in chemical engineering and biology, its impacts on other units were considered more limited. The School of Science, in particular, was said to be the "hardest nut to crack" at MIT, because it tends to be comprised of individualists who like to do things their own way. Indeed, one individual commented that it had been astounding watching the Nobel laureates in biology letting the engineers call the shots in BPEC.

Education

The driving force for BEH was education. Faculty in both biological science and chemical engineering believe that students in both fields need to be cross-trained to provide better coverage of topics these students will encounter in their professional careers: biology students need to be comfortable with new methods of analysis and data processing; students in engineering need to have an increased understanding of biological sciences. Six cross-listed, team-taught courses between biology and chemical engineering have been developed as a result of research collaborations begun through BPEC, and the number of such courses is expected to increase with the formation of BEH. BPEC had also initiated revisions in content of existing courses. The Center has developed one cross-departmental course that, although an elective, draws close to 80 biology and chemical engineering students each time it is offered.

All faculty are required to teach in their departments. Faculty noted that these cross-disciplinary courses gave faculty the opportunity to work with students from departments who typically did not enroll in their courses. Students in the two fields were also brought together by participation in Center activities; what was referred to as a "fascinating transformation" of these students reportedly followed. Undergraduate chemical engineering students were said to be increasingly enrolling in courses in biochemistry, molecular and cell biology. Graduate students in chemical engineering also enrolled in some of these courses, particularly cell biology. The biology department has begun to offer short courses for faculty from the Engineering School. The combination of training in biology and chemical engineering was said to be of particular value in the private sector.

Apart from its role in course and curriculum changes, BPEC was seen as having impacted education at MIT in more subtle ways. For example, BPEC was considered an important recruiting tool in attracting students. It was described as a "big drawing card," a large-scale and visible magnet, in getting top graduate students. The Center has also served as the base for minority recruitment, particularly through its REU program (BPEC has placed a great deal of emphasis on bringing undergraduates into its laboratories using REU and other programmatic vehicles.) The Center was also credited with bringing industrial researchers and other private sector representatives to the campus, thus giving students a broader picture of what careers in industry might be like.

BPEC's laboratories and equipment were made available to graduate students whether directly supported through BPEC or not, thus exposing students not affiliated with the Center to industrial interaction and cross-disciplinary research, as well. It also served as a networking node, helping students meet students from other departments and laboratories, thus aiding them in learning about the availability of equipment elsewhere on campus. BPEC faculty were reportedly quite open about sharing their equipment with non-BPEC faculty; students working on projects for non-BPEC faculty thus also benefited from the Center, often learning about biotechnology in the process.

BPEC reportedly supported about 12 graduate students per year, at an average cost of $50,000 each per year. At MIT, every award for a stipend must cover at least 70 percent of tuition, plus fringe benefits (26%) and indirect costs (63.5%), making the support of graduate students an expensive proposition and a major cost element in the construction of research budgets. In the Center's view, however, "that's what we're here for – to educate students."

Students were said to have a greater sense of belonging to their departments than to the Center *per se.* However, BPEC was seen as a way of networking. Students repeated a lot of group social activities through the Center that they probably would not otherwise have. BPEC was also considered a strong draw for the top graduate students, in that the students see a focused center of activity with a critical mass, a clear identity, and state-of-the-art equipment and facilities.

Since 1993 MIT has required that all undergraduates take coursework in biology. Biology was described as the "liberal arts" of science. An estimated 50% of the biology department's own undergraduates reportedly end up in careers outside of science, many finding jobs on Wall Street. MIT views itself as having a responsibility to lead in the redefinition of what engineering education is all about. It reportedly has long placed great emphasis on having undergraduates involved in laboratory experiences, and funds an Undergraduate Research Opportunities Program to encourage this. A faculty member from the biology department estimated that about 80% of the department's undergraduates work in the labs. Often, they initially take a lab course for credit, then subsequently seek out additional research-related experiences for pay.

Industry Interaction

MIT historically has had close ties to industry. BPEC was said to have facilitated this interaction, in particular helping faculty who did not have previous strong associations with firms establish these relationships. The technology transfer orientation of MIT's biology and chemical engineering departments reportedly has changed as a result of BPEC industrial connections.

Whereas about 20 years ago, only one faculty member in biology consulted with industry, today such relationships are the norm. Moreover, some of biology's best Ph.D.s now find employment in the private sector, a trend that faculty value as broadening career perspectives and opportunities. Similarly, industry is seen as hiring graduates who have worked in BPEC to do BPEC-related work. Merck has become the largest single employer of graduates from the chemical engineering department.

The Center Director described BPEC as now having a different strategy than most ERC's in its relationships with industry. Whereas most ERCs tended to go after as great a number of industrial contributors as possible, BPEC, which initially also followed this strategy, eventually learned that the life cycle of these industrial commitments was relatively short. At one time, BPEC had an industrial membership of about 80 firms, each of which paid fees ranging from $2,000 to $20,000 annually. Many of the firms were small start-up companies. BPEC eventually learned that the amount of work they were asked to do by firms varied inversely with the fee structure; small firms were described as consistently asking for help, with students being asked to perform technology transfer tasks and improving research techniques within company operations. As a result, BPEC changed its strategy. It formed an industrial research consortium with a membership fee of $25,000, with meetings convened at the Center three times each year. At the time of the SRI interviews, membership in this consortium had been holding steady at about 13, almost all of which were large companies. This strategy was also said to be helpful in allowing BPEC to leverage its relationship with these firms to secure additional research contracts, often on the order of $300-$500K per project. It was also considered useful in terms of attracting the right industrial participants – those company officials who wrote the check were the champions, and understood and appreciated both the research and the importance of the associated educational activities.

MIT's influential contacts with firms were considered helpful to BPEC in establishing its own connections. The Center's contacts, in turn, were considered helpful to the University, which is interested in developing alliances with companies. BPEC also led to the formation of a collaborative program among three of MIT's Schools (Engineering, Science, and Sloan) in connection with the pharmaceutical industry. Involvement with industry reportedly also has affected the way faculty view research consortia. Firms are seen as wanting large-scale research undertakings; to respond, faculty need to develop relationships with researchers across campus.

MIT's intellectual property rights policies were said to have initially developed during the 1930s, unlike the more recent forays into this area at the other universities included in this study. Given this long history, MIT's intellectual property rights policies were described as "very conventional" but "aggressive." MIT will patent anything that has a reasonable chance of self-sufficiency (e.g., recovering the cost of filing). The primary objective was said not to be income maximization, but getting the technology to the public. If an invention is made under a grant to the University or involved use of MIT facilities, MIT owns the invention and shares license income with the inventor.

Although the basic outline of its IPR policies is considered conventional, MIT's IP strategy is considered unique. The strategy is based on volume and a recognition that IP is a talent-based business requiring a creative technology transfer staff that is given a lot of flexibility. MIT gets about 360 disclosures annually, and receives about 150 patents and 20 to 30 software licenses per year. About 50% of these patents yield some form of IP. If MIT chooses not to pursue a patent, the rights revert to the sponsor of the research, who may give these rights to the faculty member who was involved with the invention. (MIT does not want to have these rights automatically revert to the faculty member, because of potential conflicts of interest in the event the faculty member in turn gave the rights to his own company). Disclosures for which patents are not filed tend either not to be unique or to have a limited market in terms of anyone investing in it. The policy is not to use exclusive licenses to get additional research funding. Requests for additional research funding are made only if added research is needed to bring the patent to marketability.

BPEC is not seen by the University's technology transfer office as having had a major impact on MIT's IPR policies; nor was there seen to have been any significant IP activity from BPEC. Reporting relationships may, however, have obscured the level of intellectual property activity being generated by BPEC. If a faculty member from BPEC has been involved in a licensed patent, the income would likely flow to the faculty member and the home department, not to BPEC, and it is possible that there are BPEC IP activities of which the technology transfer office is not directly aware. Industrial consortia run through the University were said also to have had no impact on the University's IPR policies. The small annual fees associated with consortia membership were said to carry no IP rights.

The technology transfer office noted that changes in IPR policy generally occur only when cases arise that "don't fit". The most radical change in MIT's IPR policy was said to have occurred in the late 1980s, when MIT got involved in a biotechnology start-up and the then-existing policy precluded exclusive licenses to firms in which a faculty member had an equity interest. This non-exclusive license policy was said to have been the "kiss of death" for a biotechnology start-up, because without an exclusive license the firm could not get venture capital. The policy was changed. There has been very little tinkering with the IPR policy of the University since that time.

Overall Impacts

Although MIT as an institution reflected many ERC-like characteristics prior to the establishment of BPEC, the Center nevertheless had significant impacts on the University. These impacts were not confined to immediately participating departments and students, but were reflected in changes of both an institutional and organizational nature within the School of Engineering, in particular, but also within the School of Science. The most immediate impact was in terms of the new collaborations forged between faculty from the departments of chemical engineering in the Engineering School and biology in the Science School. While interdisciplinary research was held to be quite common at MIT prior to the ERC, cross-college efforts were relatively rare.

The model of linkages between biology and chemical engineering developed in BPEC created a broader consensus on the campus of the utility of increasing the understanding of fundamental biological research and methods within engineering more broadly. In 1993, the University began to require that all undergraduates, including those in engineering, take coursework in biology. By 1998 at the time of the SRI site visits, the University was in the process of setting up a new organizational structure within the School of Engineering to formalize the role of biology within the entire engineering curriculum, an effort viewed as largely emanating from lessons learned from BPEC and the desire to embed these lessons in the educational structure of the School of Engineering writ large. Biology had come to be seen as the fundamental core underpinning a great deal of the interdisciplinary problem solving that would be required for engineering advances of the future.

The MIT case is interesting in that it demonstrates a situation in which even a University already encompassing many ERC-like characteristics can derive benefits from the ERC that lead to broader institutional changes within the University as a whole. In the case of MIT, these changes were primarily reflected in the area of education, but also in broader interdisciplinary research collaborations that crossed the bounds of the Schools of Science and Engineering. That being said, the departments at MIT clearly remain strong bastions of disciplinary based research and education programs, sufficiently embedded in promotion and tenure practices that few junior faculty found it prudent to participate extensively in the ERC. Indeed, it was just this tenacity of the departmental structure that led the University administration to adopt a new organizational structure for BEH that would insulate it from the parochial hiring and promotion practices that hold sway in individual departments.

MISSISSIPPI STATE UNIVERSITY: CENTER FOR COMPUTATIONAL FIELD SIMULATION

Background and Overview

Mississippi State University (MSU) was founded in 1878 as the Agricultural and Mechanical College of the State of Mississippi, one of the national land grant colleges established under the Morrill Act of 1862. Since then, it has grown to be a comprehensive, doctoral degree-granting University that offers a broad-based curriculum in the sciences and engineering, the arts, and technological disciplines. It is a Research II University in the Carnegie Classification, with total 1999 R&D expenditures of about $110M, of which industry accounted for about 7%, ranking it 86th and 71st, respectively, among all U.S. colleges and universities. According to site visit interviewees, the University ranks 4th among East South Central institutions in R&D expenditures, and first in the State of Mississippi.

With total undergraduate and graduate enrollment of about 16,000, MSU is (next to Montana State University) one of the smallest of the public universities associated with the ERCs included in this study. About 13% of the University's bachelor's degrees and 8% of its doctoral degrees conferred in 1999 were in the engineering fields. The electrical engineering program was the only graduate engineering program at MSU rated by the NRC (at 107th of 126 programs rated), and its overall graduate program is not rated by *U.S. News*.

The University was said by interviewees to be a product of the South. Because Southern institutions paid very little attention to research for many years, they are now in a position of having to play catch-up. Little understanding of the importance of research was said to exist in the Mississippi State Legislature even today. Agricultural research and technical assistance – "going out and helping the farmers" – is considered a much easier case to make in trying to obtain state funding. MSU also paid a price for the state's fierce opposition to the civil rights movement of the 1960s. For many years after the civil rights movement, MSU found it very difficult to attract faculty to its campus who had been born or educated outside the South. As a result, most of the faculty hired to teach in the University were local, and many of these had been educated in the local universities as well. This inbreeding created a narrowness of perspective that the University has been trying to correct. MSU has been endeavoring to recruit faculty from outside the South and from abroad in order to foster a more cosmopolitan feel. This was said to have been especially difficult due to the University's low faculty salary scale. While the University was said to rank fourth in sponsored research among East South Central universities, it reportedly ranks 26th in faculty salaries.

At the time of the SRI interviews, there was a new President of the University, then in his second year. The new President was said to have made his goals very clear since his first days on the campus, and to have made quite a difference already. Among his goals is to move the University into the top 50 in terms of research funding. MSU's latest ranking was 86th in 1999. He reportedly recognizes that faculty salaries are entirely too low and has taken steps to increase them. He also recognized that MSU does not have a sufficient number of faculty. In his first year, the new President went to the State Legislature and obtained approval for a 26% increase in the University's budget, an accomplishment that he repeated the following year. In his first year, he was able to add approximately 45 new faculty positions to the University. The potential to advance the University's research enterprise was said to be the top criterion for approval of new positions, although the President is also reportedly emphatic about making MSU the top teaching university in the five-state area.

The Center for Computational Field Simulation (CCFS) was established as an ERC in 1990 as part of the fifth cohort of ERCs. At the time, there was one other major center on campus, the Diagnostic Instrumentation and Analysis Laboratory (DIAL), which remains the principal center of research activity on the campus other than the ERC. The University had submitted an earlier proposal for an ERC, in 1987, based largely on research undertaken by DIAL, but the proposal was not successful. The idea for the CCFS came about because the University was in the process of setting up a Center for Advanced Computing with an expected $10M in research funding from Congress, plus an additional $5M for a building in the new Technology Park. The building was constructed with the $5M, but the $10M for research operations never came through. This left the University with a building but no operating funds for the research that had been expected to take place in the facility. According to the Vice President for Research, this mode of developing new research areas is standard within the University. The University attempts to secure an initial Congressional set-aside (through Senators Lott and Cochran, both of whom were said to be major supporters), and then expects to successfully compete for open, merit based-awards on their own once the area has become sufficiently established.

The ERC initially hired people specifically to work in the ERC, on either nine- or twelve-month contracts. This appointment system was said to have created a disaster. Now, the Center just tells potential new hires about the opportunity presented by the ERC – the space, the facilities, the equipment, the support – and a number of new faculty are drawn to the opportunity. This is seen as a major contrast with the mode of operation of DIAL, the other major center on the campus. DIAL is now almost totally staffed by research faculty because of the barriers the departments set up to faculty participating in it. Indirect Cost Recovery return issues, excessive teaching loads, and promotion and tenure considerations were said to have created an absolutely negative incentive for faculty participation. As a result, DIAL's effects on the University and the individual departments have been quite limited, despite the $60-70M in research funding it has generated over past 18 years. The ERC was said to have far greater impact, in that it perceives itself as a University research center and operates directly with departmentally based faculty.

The ERC began operations in the building originally built for the Center for Advanced Computing in the new Technology Park. There were said to have been compelling reasons for placing it off campus. The local economy was and remains depressed, and CCFS was seen as a magnet for attracting other tenants. In fact, the ERC *is* credited with helping to draw other research facilities, including some industrial ones, into the Technology Park. However, there are felt to be distinct drawbacks to the ERC's location. It is less visible to others on the campus, it is less interactive with the academic departments, and the students are more isolated from other students and their home departments. One interviewee based on the main campus reported that "If people could just walk over there it would be great, but the thought of driving over there and coming back and having to find a new parking place is a real disincentive."

Despite such limitations due to location, there was reportedly little question that the ERC has had a major impact on MSU. First, it is seen as a tremendous help in recruiting high-quality new faculty; all new prospects are taken through the Center, whether they will be associated with it or not. Second, the ERC's reputation has reportedly also helped increase the quality of the students they are able to recruit, both undergraduate and graduate. Average entering ACT scores have been rising, and the ERC is credited in part with this development. Even so, it was said to be an uphill battle for the University to increase the number of out-of-state students. The ERC's REU program has helped to provide some access to students from other institutions and other states, but recruitment is still a difficulty. Third, it is increasing the quality of the students graduated by the University. The Center itself was said to be producing high-quality graduates; in addition, the secondary impact on students who merely see their colleagues working with the Center was said to have been substantial. Fourth, the Center is credited with increasing the campus's research emphasis. It is reportedly teaching young faculty how to write successful research proposals, as well as helping attract new faculty with stronger research interests and backgrounds. Finally, many reported that the impact on the graphics department, which has become closely linked with the Center, might be one of the greatest impacts of having the ERC on campus. The graphics department has won numerous prizes. Overall, while the ERC was said to have had a direct impact on only a small number of departments, its presence reportedly sends a message all across the campus that MSU is a major player, and confidence has been placed in the University by NSF. The ERC was said to serve as a reminder that the University often sells itself short by thinking that it cannot possibly compete with the "big players."

Engineered Systems

The Center's research efforts are directed at reducing the costs of conducting field simulations. In the early 1990s, the cost to do a simulation of an aircraft was about $6M, because it took six months to even set up a problem with the enormous number of grid points that had to be computed. The available computing power simply was not sufficient. However, the Center has looked at the way computing capabilities are evolving, and has been attempting to exploit the computer revolution, in terms of both hardware and software. For example, NASA called the Center about a problem with a door hinge that was falling off a parachute hatch. The Center created the grids and solved the problem within 24 hours. In hindsight, they look back at this and say, "Wow, this is really what the mission of the Center was and has been." They have invested heavily in the integrated CFS system environment, which in turn is considered vital for the Center's program of technology transfer and industrial collaboration. The Center now relies on industrial participation in defining the applications-driven problems.

The Center reportedly had difficulty communicating to NSF about the exact nature of the basic science it conducted. Essentially, they use funding from the Office of Naval Research for the end deliverables, but they use NSF funding to support the underlying science. Faculty appear to appreciate the systems approach, in that they can still go into the back room to "play," doing basic research, but the research is sufficiently applications-driven in terms of the overall system that they do not end up getting a very elegant solution to a problem for which there are no needed applications.

Strategic Planning

Apart from the ERC itself, strategic planning in the University prior to arrival of the current President was said to have been non-existent. The new President has implemented such planning on a number of levels, in developing their current hiring plans, for example. Out of the 800 or so faculty at the University, only about 100 were said to be really active in securing research funding. As a result, it needed to hire new faculty to bring in new research funding. To successfully recruit in turn required equipment, colleagues, infrastructure, and an environment in which collaboration and research is encouraged. MSU also developed a new evaluation effort to help them decide how to allocate new positions to those areas where they have the best chance of success. The evaluation effort is very strategically focused, involving both qualitative and quantitative indicators.

MSU has seven objectives in its overall strategic plan, and the ERC activities were said to dovetail with each of them. One is to improve its rankings. MSU is in the third quartile in *U.S. News*. The ranking is considered largely a matter of perception, and one that they need to improve. A second is to continue to improve undergraduate education. A third focuses on graduate studies in six major areas that will impact the State, the nation, and the world. Outreach to K-12 students and to industry are also among the objectives, and these are directly relevant to the role of the ERC. Another objective is to improve and develop their research facilities, which is very important in attracting quality faculty. Partnering with industry and government agencies is another objective, and the ERC is considered a key player in this area also.

The ERC itself has been using the NSF three-tier approach to their strategic planning. Conceptually, they start at the top level, engineered systems, and move through the technology level, down to the basic knowledge level. But they move from the bottom up in terms of deliverables. Faculty participate in the ERC's strategic planning process, which gives them a chance to focus their research as well as to interact. ERC faculty noted that the strategic planning process facilitates and focuses communication among faculty. It lets different research specialties and interests interact on many different levels. The faculty emphasized the informal nature of their communications and involvements in the Center's strategic planning process.

Interdisciplinarity

The ERC involves faculty from several departments in the College of Engineering (aerospace, civil, computation, computer and electrical, and mechanical engineering and computer science) and the College of Sciences (mathematics and physics). The ERC itself is considered a truly interdisciplinary research operation, placing faculty from a number of different disciplines in the same building, which enhances their interaction. Faculty associated with the ERC reported that conducting interdisciplinary research is "hell on wheels," but it works. They do not speak the same language as their departmental colleagues, and they direct their research to different audiences. The ERC was described as having the ability to have applicators interact with tool developers, followed by visualization. The mix of students from different disciplines working in the ERC building was also seen as leading to the sharing of ideas and techniques.

Prior to the establishment of the ERC, there was reportedly very limited interdisciplinary, cross-departmental research on the campus. The ERC was said to have had a definite impact on cross-departmental research within the College of Engineering, forging new ties between faculty in aerospace and mechanical engineering and between mechanical and electrical engineering, in particular. Still, such collaborations were said to be nowhere near the scale of what goes on in the ERC itself; faculty in mechanical engineering, where team research as opposed to individual PI grants has always been the norm, reportedly still think primarily in terms of intra-departmental collaboration. While interaction with the College of Sciences is reportedly quite limited as yet, this was seen as being partially due to the enormous amount of building renovation that had been taking place on the campus, causing a great deal of disruption. It was felt that the ERC has the potential to attract additional faculty from the College of Sciences once more people become aware of the Center's work.

The ERC was described as having made disappointing, intermittent progress in changing MSU's culture. Several times after progress had been made, the installation of a new dean or department head led to retrogressive steps. There was said to be considerable institutional inertia that has built barriers to the approaches to engineering research envisioned by the ERC Program. There are tensions between the departments and the ERC over the awarding of credit for ERC activities in promotion and tenure decisions, as well as in the distribution of indirect cost recovery. Some department heads see faculty participation in the ERC as part of normal departmental activities; other department heads see ERC activities and research outputs as separate from departmental research.

The University has a uniform promotion and tenure questionnaire for all departments. It calls for an excellent rating in one of three areas (research, teaching, and service) and satisfactory in two for promotion to associate professor and excellence in two and satisfactory in one of the areas for promotion to full professor. The ERC attempted to augment that form with additional questions that relate more specifically to center type activities, but thus far has been unsuccessful in its efforts. The Center has reportedly not lost any promotion and tenure battles, but there were said to have been some absolutely vicious battles. One of the main reported problems is that department heads do not directly see the results of junior faculty members' involvement in Center research, because it gets swallowed up in the larger Center output. Another relates to "credit": a previous dean reportedly had no difficulty with the concept of dual credit for the ERC and departments. But the new dean is seen as seeking to hold departments more accountable for the development of their faculty, and this is being interpreted by department heads as costing them if their faculty run their grants through the ERC.

There are some indications of change, however. Recently, the definition of what constitutes P&T eligibility had been expanded to include non-tenure track research staff. This revision apparently was largely in response to grievances from ERC research staff about not having procedures for promotion. In addition, a compromise appears to be emerging regarding P&T criteria themselves to incorporate ERC-type activities. This has broader implications than for ERC faculty per se: i.e., there was said to still be a need to move the ERC-like interactions and activities into the departments themselves, and revisions to the P&T criteria may well provide some incentive for this, or at least minimize one existing disincentive.

The University's financial formula apportioning indirect cost recovery was said to have a strong effect on the relationship between departments, faculty, and centers. The current indirect cost recovery policy of the University is that 60% is retained by the University and 40% goes to the department. If a center is involved, then the department share goes down to 20% and the center gets the other 20%.

Education

The College of Engineering is comprised of five departments: electrical engineering, computer engineering, aeronautical engineering, computer science, and computational engineering. There are no departments of chemical, mechanical, or civil engineering, although there is a general Ph.D. that encompasses some of these areas. The computer science department was moved into the College of Engineering from the College of Sciences just about five years ago. The computational engineering program was developed directly by the ERC.

When the Center started the computational engineering program, originally as an M.S. and then a full Ph.D. program actually administered by the Center, it was reportedly the only one in the country. Now there are a number of others, but they are generally more focused on computational science rather than engineering. Getting the computational degree program established was considered a significant accomplishment of the ERC. Now there is reportedly one other NSF/ERC that actually administers an educational degree program, but it was said to be more of a training program than a research-oriented degree.

At the time that the Center established the computational engineering Ph.D. program, MSU did not have a Ph.D. program in mathematics, and it was reportedly one of only two land grant institutions in the United States that did not offer a mathematics Ph.D. Even so, it was having difficulty getting such a program approved by the State Legislature, because there was one at the University of Mississippi and a need was not seen for another. Once the Center was able to get the computational engineering program in place, however, the argument was made that it made no sense to have a computational engineering Ph.D. program without offering a mathematics Ph.D., and they were able to get this through the State Legislature without any difficulty. In this sense, the ERC is credited with helping to start the mathematics Ph.D. program, as well as that in computational engineering.

The development of the Masters of Fine Arts in Electronic Visual Imaging was also considered a direct spin-off of the ERC. It was reportedly one of the only programs in the country that has involved collaboration between a College of Arts and Humanities and a College of Engineering. The artists and architects reportedly did not initially know about a type of machine available in the Center until the Center brought them in and showed it to them. They immediately saw the utility of it for their own work, and the architects are now doing virtual reality and the artists are taking a virtual trip to California with the use of an ERC computer. Some saw a drawback to the relationship of the graphics program to the ERC, however, in that the program had been drawn too closely into the ERC rather than maintaining its independence. In addition, some considered the graphics program a distraction in that it did not contribute to the core mission of the ERC. Most, however, considered this linkage a major benefit to the University as a whole.

At the time of the SRI site visit, there were 20 M.A. and Ph.D. students enrolled in the computational engineering program. Computational engineering is very computer applications oriented, whereas electrical and computer engineering are much more oriented toward computers and how to build them. Some commented that the Center really should be called an Engineering Research and Education Center, because the research gets transferred almost directly into the education, to the students. The Center always has sufficient funding to include undergraduates, although research is typically missing from undergraduate education on campus. One interviewee reported that, “You can see the lights go on when undergraduates start working in the Center.” One faculty member who has for the most part worked with Ph.D. students, and only rarely with M.A.s because he was not sure he could get out of them what he felt was needed, has found that the undergraduates involved in the Center are really very valuable. Nevertheless, this is still considered a rare situation on campus.

The Center reportedly also has a large commitment to minorities and outreach. It has a link with an NSF Center for Research Excellence in Science and Technology, part of a program established by NSF specifically to encourage research improvement in minority institutions.

On the negative side, several individuals commented that the ERC’s computational program detracts from the educational programs within other departments. As an Engineering Research Center, the ERC needed to develop some courses, so it developed a computational engineering course, but this was said by some to have been essentially a duplicate of an existing course, just labeled differently. Then it began to draw some students, but essentially by taking away students from elsewhere. Given MSU’s difficulties in attracting students, some feel that the entire computational program has resulted in a decline in the number of students in other departments, many of which are desperate for more students, particularly at the doctoral level.

Industry Interaction

Of its total R&D expenditure of $110M in 1999, funds from industry accounted for about 7%, down from a high of about 11% in the years 1990 to 1992. Industry interaction is reportedly fairly common at MSU, although generally not viewed as favorably as more traditional federal research grants in tenure and promotion decisions in most departments. As recently as 1995, the Office of Sponsored Research was said to have been unable to handle fixed-price contracts, which is what industry generally wants, although that situation has now improved. Most of the local companies are small or offshoots of large corporations that conduct their R&D elsewhere. They generally are interested only in technical consultations, not research per se, so the ERC has to look for most of its industrial support elsewhere. Because the Center’s technology has been very expensive, it is primarily the large defense contractors that have been interested in it.

Until the early 1990s, there was a Mississippi State law that prohibited any employee from achieving personal financial gain through his employment at a state university. While technology transfer was not prohibited, there was little incentive for it. Then, in about 1992, the Mississippi State Research Consortium initiated a piece of legislation called the Mississippi University Research Act, which encouraged the involvement of universities in economic development and changed the law regarding financial gain from intellectual property.

In 1994, MSU owned zero patents, had very few royalty bearing licenses, and no central management structure for IPR. Some patents had been filed by individual departments, some by Colleges, but there was no central legal or management structure in place. However, since 1994, every metric MSU has used to track their IP has gone up. They have been participating in the AUTM[12] patent survey every year since 1994. They now have about 24 patents and roughly 15 royalty-bearing licenses in place. IP income has been fluctuating from a low of about $100,000 to a high of $275,000 in recent years. They have not yet reached the AUTM national average for IP income/research dollar, but that is their goal. They have been working on changing the mindsets of faculty to patent the results of their research rather than simply leaving it in the public domain.

Reflecting its traditional research emphasis on agriculture, most of MSU's patents relate to agricultural processes. MSU has a mandate to go out and assist the farmers, analyze the soil, etc., and so they have always had an outreach attitude. While that sort of outreach has not been mandated in the College of Engineering or the College of Arts and Sciences, the ERC was said to have been the most productive of the various departments in terms of non-agricultural technology transfer to the private sector, copyrighted software in particular. The ERC has licensed five copyright agreements to the private sector, each one to a small company, and every one of them is returning royalties. One of the companies is a member of the ERC, the others are not, but were started by people who used to be graduate students in the ERC. Some ERC faculty are also involved in the companies. The University's technology transfer office is just now processing one patent for the ERC.

The most recent development in industrial interaction is perhaps the most notable: as a direct result of its membership in the ERC, Nissan Motors has opened an Advanced Vehicular Navigation Systems Institute near the campus. The Center's long-time Director has been assigned by the University President to be the point man for the University in developing the involvement of the University in the research and education that will be conducted in the Institute. This facility is seen as a major contribution of the Center to economic development in the state.

Overall Impacts

Mississippi State is the second smallest of the public universities housing the ERCs included in this study. It is also unique among this set of universities in being a product of the Deep South, with the attendant political and historical legacy of low state commitment to public higher education and racial discrimination. The recent objective of becoming a major research university, coupled with a new University President who is actively seeking to change the University's profile at a time when the ERC is the most visible research entity on the campus, makes the ERC a very important component in the University's strategic plans. These plans include attracting a greater volume of research dollars; attracting a higher number of higher quality, more research oriented faculty; attracting a higher number and higher quality of students, both graduate and undergraduate. To do so, the strategic plan recognizes the importance creating

[12] Association of University Technology Managers

an environment that will help attract the research funding, faculty, and students it seeks: improved undergraduate and graduate education, higher quality research facilities, higher salaries.

The ERC was said to have contributed to the achievement of all of these goals. It is credited with having helped to recruit high-quality new faculty and graduate and undergraduate students, to have increased the quality of the graduates being produced, increased the research emphasis on the campus, strengthened industrial alliances leading to economic development, and forged research collaborations across departments and colleges that increases funding opportunities from both federal and industry sources. The ERC is thus very highly valued as an important player within the University, and the ERC Program goals are, in turn, strongly adopted and supported by the University administration.

That being said, the ERC's progress in changing the deeply embedded culture at MSU was described by some faculty and administrators as intermittent and disappointing to date. Promotion and tenure policies are still seen as inhospitable to strongly research-oriented accomplishments *per se*, let alone interdisciplinary research efforts that cross departmental or college bounds. Some of the ERC's educational efforts, such as the links established with the graphics department, the new Ph.D. in computational engineering, and even the new mathematics Ph.D. for which it was said to be largely responsible, are not widely accepted on the campus as having represented major strides for the University. Since students, particularly at the doctoral level, are viewed as a scarce commodity, the ERC efforts to attract students were often viewed as "robbing Peter to pay Paul".

MONTANA STATE UNIVERSITY: CENTER FOR BIOFILM ENGINEERING

Background and Overview

Montana State University at Bozeman (MSU) was established in 1893 as the land grant institution for Montana. Since then, it has grown into a comprehensive, multi-purpose state-controlled university, with expanded programs in the liberal arts and professional areas, while maintaining its traditional emphasis in science, engineering, and agriculture. Total undergraduate and graduate enrollment in the 1999 academic year was just under 12,000, making it the smallest of the public universities associated with the ERCs included in this study. The College of Engineering accounts for about 12% of total graduates at the bachelor's level and 6% at the doctoral.

MSU is a Doctorate II University, the only institution in this study not ranked as Research I or II in the Carnegie Classifications. In 1999, the University ranked 128th in total R&D but 83rd in industrially funded R&D among all U.S. universities and colleges. In that year, industry was the source of about 13% of Montana State's $55M total R&D. Mechanical engineering, a department with very little involvement in the ERC, was the only one of its graduate engineering programs rated by the NRC in 1993. MSU is placed 148th (out of 179 institutions) for cell and developmental biology, but no ranking is provided for those aspects of microbiology most directly connected to biofilm engineering. The University's overall graduate engineering program is not rated by *U.S. News*, nor is its program in microbiology.

The Center for Biofilm Engineering (CBE) was established in 1990 as part of the fifth cohort of ERCs. The Center originally grew out of an Institute for Process Analysis (IPA), which had been in existence at MSU since 1986. The IPA included a few microbiologists (the current ERC Director, a microbiologist, was involved), but primarily consisted of engineers, a characteristic that carried forward through the earliest years of the ERC. Since then, the ERC has come to be a strongly integrated cross-college operation, with extensive involvement not only of the microbiology department but other departments in the College of Sciences as well.

The University was said to have worked hard to obtain the ERC. The State, which had supported the IPA, was interested in expanding it to an ERC and helped by committing some financial support. The impact of the Center is considered substantial on both the College of Engineering and the entire institution. Part of the reason that the ERC's impact has been so great is the size of the institution. The ERC is a "big" operation in such a small institution. The CBE's roughly $4-5 million annually in grants and contracts from all sources has represented 8-10% of the University's total R&D funding in recent years. The ERC was often cited by MSU's president and administration as an example of how to build a center of excellence. There are two other centers on campus – the Mountain Research Center and one in optical laser diodes, but no other center at MSU has the financial clout of the CBE.

An industrial base was already in place with the IPA prior to the establishment of the Center. The cluster of 12 key researchers that MSU felt was needed for the Center was also in place in the University. Nevertheless, NSF felt that for MSU to effectively host an ERC, it needed to add 14 new faculty lines, which the Provost subsequently approved. Although all 14 of these positions were for faculty who could work in the Center, they were distributed over a number of departments, including physics, electrical engineering, microbiology, and others. As part of this initial package, the Provost provided the Center Director with four years of salary and start-up funds so that the Center could recruit a Cal Tech graduate to the chemistry department. The new faculty member brought with him a specialized machine from the Jet Propulsion Laboratory, and set it up in what is basically a shack on the campus. He continues to conduct research using that machine in that shack, and his interests have continued to coincide with those of the Center. In other cases, the Provost and the Vice President for Research provided anywhere from 1½ to 4 years of faculty salaries for new hires associated with the ERC, with the net result that the Center actually ended up getting 16 new faculty lines.

The Center was said to have had an impact on a number of departments. There are now 29 faculty associated with the Center drawn from 11 departments, with students drawn from 13 departments. Department heads are now generally supportive of the Center, although that has not always been the case. At the Center's outset, department heads had to invest fairly heavily in the Center by giving faculty released time from teaching and other departmental activities. At the time of the SRI interviews, most of the faculty time in the Center was underwritten by the Center itself, and as the students in the departments also get support from the Center, it was generally considered a win/win situation for the departments.

The ERC is frequently cited when the topic of MSU's standing as a research institution arises. It is the largest activity on campus, is well thought of, and is known by all. Collaboration is a way that researchers can make a difference in a university that is small and geographically remote from larger research centers, and the Center was credited with helping to create such an environment at MSU. The ERC has involved participation by almost every academic unit of the campus except art and architecture. The perception is that at a much larger university with many research centers, the impact of an ERC would not be as great because it would get lost among all the other centers and research activity. Given the size of MSU, however, the CBE has a major visibility. Faculty who are not associated with the Center realize that they can tie in with the Center to get the research and administrative expertise needed to help sell proposals. The ERC also has very good equipment which is generally available to non-ERC faculty. The ERC is seen as having a big impact on the College of Engineering, which traditionally had not been highly research-oriented. The Center is cited as an example of MSU's commitment to research and its standing as a national center of excellence in recruiting faculty, especially in efforts to hire more established researchers who require sufficient confidence that they will be able to thrive and receive support in the MSU environment.

Engineered Systems

The Center reportedly functions entirely on a systems basis. Three civil engineers have recently become connected with the Center to take advantage of its systems approach. The Center's test-beds are another attraction. Several faculty said that the ERC was responsible for a change in attitude regarding the formulation of research questions. Previously, they would say, "let's investigate this because no one else has done it." Now they say, "let's investigate this because no one else has done it AND we have a problem that needs to be solved."

Strategic Planning

The University has a long-range plan and a long-range planning committee. As a land grant institution, the University is always faced with a question of balance between teaching and research. The ERC was said to have been an incentive for the University to redefine its objectives and reexamine what the balance should be. The University also has an Industrial Advisory Council, and measures its objectives against what this Council recommends. The University's mission calls for it to provide education, research, and outreach, but the first of these is education. The ERC embodies all three.

The Center started with a strategic plan at year one, but annually since then has reviewed its plan, which continues to evolve. The Center sees itself as having an obligation to reformulate strategic objectives each year. Although this approach is time-consuming, it helps individuals to clarify their thinking about the direction in which they need to go The Center was said to provide a force in shaping people's research agendas. This thinking is also very driven by the international contacts and what is known about what foreign research centers are doing. The extensive interaction with industry also shapes the strategic plan. In a sense, the Center's agenda is driven by all of these different perspectives affecting the thinking behind which direction to take.

Interdisciplinarity

The University was said to have changed significantly during the life of the Center. The Center brought disparate groups more closely together and there is now an increased receptiveness to interdisciplinary collaboration now on the campus as a whole. Interdisciplinary research is now considered "doable." There are more proposals going out that cross departmental lines, largely because the Center showed it could be done. The cross-departmental structure of the ERC was thought to have been important in enabling the College of Engineering to become much more integrated than previously.

The walls between disciplines, especially between engineering and the sciences, were perceived as very high at MSU when the Center was first established. In the early days of the Center, when the original Center Director was an engineer, it was very difficult to get the microbiology department head involved; he refused even to participate in the NSF site visit. This was a very difficult situation, when everyone realized that it is "ludicrous" even to think of doing biofilm research without microbiology. Relations between the ERC and the chemistry department were strained as well. The chemists worried that the Center was picking up students that the department had spent money recruiting; the number of seminars run by the Center was considered an issue in making students switch allegiance. While there had always been some interdepartmental collaboration within the Colleges, there was a real chasm between the Colleges of Science and Engineering.

When the new ERC Director, a microbiologist, replaced the original Director following his sudden death, the Center was almost entirely comprised of engineers and he had to really begin working on bridging this chasm. He first hired a chemist, then a physicist, then a microbiologist, expanding the number of faculty lines for these departments. Ultimately it is the departments that give the degrees, not the Center, so the students belong to the departments. It is the departments that give tenure, not the Center, so the faculty belong to the departments as well. The new Director therefore realized that it was necessary to gain the support of the departments.

There is still some bitterness about the ERC on either side of the sciences and engineering wall, but this was attributed largely to a University administrator who is viewed by some as not particularly a fan of engineering. Adopting the view that most of the Center's output is due to a few top-notch scientists involved in the Center, he refused to double-credit the engineering departments with the Center's research funding. The credit situation in internal annual performance reviews has generated a fair amount of disagreement about how to treat settings in which the level of research grants and contracts received by a department may decline while those received by the Center increased. Department heads feel that their departments are not getting credit for work done by their faculty that happens to be routed through the Center.

Apart from credit for research dollars, indirect cost recovery (ICR) policies have had a heavy influence on the relationship with the departments. It was clearly understood at the beginning of the ERC that a certain percentage of the ICR would go to the departments. The University gets a 39% overhead, of which half comes back to the Center while the other half goes to the VP for Research, with the departments getting a nominal amount. However, the usual situation is that the VP for Research gets 50%, 30% goes to the department, 10% goes to the individual investigator's own account, and 10% goes to the College. This difference in how ICR is handled with the Center also originally contributed to tensions in the relations with departments that had to be overcome. One of the department chairs went to the ERC Director and requested that the ICR be split between the department and the Center on the basis of the joint appointment splits. The Center Director agreed, but the faculty from that department objected, saying that all of their research is conducted through the Center and therefore all of the ICR associated with that research should go to the Center as well. Individual grants run through the Center are handled somewhat differently. A split between the departments involved and the Center is negotiated on a grant-by-grant basis. PIs are beginning to realize that they need to take part in these negotiations, and are now starting to play a role.

Promotion and tenure criteria represent a third area that often affects cross-department collaboration. At MSU, promotion and tenure committees are formed entirely from within the individual department. The College of Engineering was said to be much more open to collaborative research in its promotion and tenure decisions than is the College of Sciences. The Center Director is aware of this pattern, however, and to recruit people, knows he must clear that hurdle. He makes a point of writing supporting letters when faculty associated with the Center are in a review process. One instance was pointed to in which an individual in the College of Sciences got tenure but not promotion, because he was thought to have done too much collaborative work. Some said that lip service was given to interdisciplinary work within the College of Sciences, but when it comes right down to it, promotion and tenure is judged on the basis of independent research. In engineering, however, interdisciplinary work was thought to be much more acceptable. In some ways, association with the ERC was thought almost to create a bias in favor of tenure, as there is a view that the ERC would not have anyone associated with it who is not strong.

Education

Contribution to education at both the graduate and undergraduate levels was widely seen as central to the Center's mission and impacts. The Center was said to be a strong influence in recruiting students to the University. University recruiters bring students around to see the Center, because it looks attractive and there is always a lot of activity. The Center has particularly influenced recruiting in those departments most closely aligned to the Center (microbiology and chemical and civil engineering). Many projects in the Center that involve students are interdisciplinary, and the College of Engineering is trying to extend that model beyond the Center.

The Center has over 40 undergraduates associated with it, including about 8 REU students from other campuses. NSF has suggested that the Center hold a national competition for its REU students, but the Center prefers to focus on students who have a great interest in the interdisciplinary and biofilms areas. The REU program has been a relatively effective tool for attracting graduate students, with five of the Center's REU students having now come back for graduate school.

NSF wanted the Center to have about an equal number of undergraduate and graduate students, so the Center now has about 45 of each. ERC faculty were worried when in about 1995, NSF said that the Center needed to have three times the undergraduates in their labs that they then had. As it turns out, the graduate students mentor the undergraduates in the same way that faculty mentor the graduate students. As a result, the increase in undergraduate students has not increased the burden on the PIs, but has instead been considered a benefit. During the year, the undergraduates tend to have so many course credits they have to fulfill that it is difficult to give them very much laboratory work, but in the summer, they are practically indistinguishable from the graduate students.

Many influences are leading to greater involvement of undergraduates in the labs, but the ERC was considered the first on the campus to do this. Overall, there has come to be a much greater emphasis on undergraduate research at MSU. There is now a Coordinator of Undergraduate Research, largely due to recognition across campus that the Center was doing a very good job of integrating students into research projects. Because it had always been a high profile part of the Center, it made other people think of doing it also.

Undergraduate students commented that there were few University programs other than those of the Center where they could work on both engineering and microbiology simultaneously. The interaction with people from entirely different disciplines was considered a major plus of the ERC. Students explained that microbiology majors end up learning from engineering students, and vice versa. Students also found it valuable to interact in the laboratory with students at different levels – sophomores interacting with juniors and seniors, these in turn interacting with graduate students. Although students have their own individual projects, there are usually a diverse set of people working in any one laboratory so that they end up interacting and learning about other disciplines. And while there are a number of different laboratories throughout the campus in which ERC-related research takes place and although ERC-affiliated students therefore often work in different laboratories, they end up all coming together in seminars and other meetings associated with the Center. Students also found the poster sessions and other presentations they give in connection with the Center a major advantage of participation in Center activities – they noted that the Center has a specialist in graphics and visual displays who works with the students and helps give their presentations a very professional look. Reactions of graduate students to working with undergraduate students were somewhat mixed: some undergraduate students were said to require a lot of time and do not really have a feel for research.

Students *not* associated with the Center seemed to be generally aware of seminars and other activities taking place in the Center. They seemed a bit surprised, however, by the amount of hands-on laboratory experience the Center students were getting, which they learned of during our joint focus group involving both Center and non-Center affiliated undergraduates. The students not affiliated with the Center had generally had far less interdisciplinary interaction than had their Center-affiliated counterparts, which would indicate that the ERC goal of undergraduate involvement in research teams has not yet widely taken hold on campus.

For graduate students, one of the chief advantages of being associated with the Center is the amount of cross-disciplinary interaction it generated. Most of the Center's labs have both engineers and microbiologists working in them, and they learn from one another. The Center also runs two courses in biofilms, one of which is required for students associated with the Center, and both courses generally have about half engineering students and half microbiology students. Graduate students also were generally enthusiastic about the interaction with industry that was associated with the Center. Microbiology faculty said that the traditional perception was that if one's students did not go into academia, the faculty had failed. The culture in the department has changed so that a student's placement with industry is now considered a positive, whereas previously it would have been considered a negative. Many students now realize that there is interesting work going on in industry and prefer to accept jobs in the private sector.

Industry Interaction

Interviewees noted that there has always been a lot of industry involvement at MSU. Funds from industry generally accounted for 12-14% of the University's total R&D over the last decade.

MSU is geographically distant from industry, and consequently is reported to make special efforts to stay in touch with industry. Industrial representatives are on almost all of the University's advisory boards. The University was said to be the number two source of engineers for Boeing, and is also an important source for Hewlett Packard, Techtronics, and a few other large companies. The Center had that tradition to draw on, but it has enhanced this reputation, being even more highly regarded as an institution that trains students with the skills and orientation to work in industry. This reputation is especially important, because little industry is located in Montana. The Center wanted to get a number of small Montana companies involved with the Center, but many of these companies reportedly could not afford the $15,000 membership fee. Therefore, the Center formed a Montana Consortium so that these small companies could jointly pay the membership fee. About a third of the Center's companies are Fortune 500 companies, which often support sponsored research with the Center, in addition to their membership involvement. The smaller companies are primarily in the environmental area, and conduct research supported by SBIR grants with the Center. The Center was reported to have always had a very synergistic relationship with companies.

The Center recently set up a Biofilms System Training Laboratory. They were able to justify a University building bond if they included some training among the facility's prospective uses, so they do have students working in the laboratory, although its primary purpose is for companies to use for testing.

Intellectual property rights have been of an issue for the Center. The Center's a basic membership fee accords no rights to any patents obtained by the Center. For an additional fee, companies have the right to apply jointly with the University for the patent. Five companies have been involved in the Center's research on souring, and the work is considered a trade secret. Most of the work involved technicians, but three students were involved and they were able to get their theses out of this work, even though it was proprietary. However, two of the Center's larger company members are suing one another about research results that came out of the Center.

The University has established a Research and Development Institute, an arms-length foundation that licenses the University's products. It also set up (in 1990) an IPR Office in the Office of the Vice President for Research. This Office, known as the Intellectual Property and Technology Transfer (IPATNT) office, deals with issues relating to confidentiality, patents and licenses. IPATNT reviews *all* sponsored research project proposals for confidentiality and licensing issues. The Office has considerable activity that emanates from the Center, and exists in part because of the Center. The University also had to establish a Facilities Use Agreement because of the ERC. It specifies whether or not industry can use the facility, how much it will cost, when, etc.

In general, people associated with the ERC considered the IPATNT office very helpful – but sometimes it was seen as an adversary. The University wanted the Center to file a patent on one of its technologies developed in cooperation with some other universities. But the Center Director persuaded them that they should take a cooperative approach rather than go it alone. The Center Director thinks that patents actually have an adverse impact. The Center operates on a very wide scale, with almost every paper having at least ten authors and almost all involving cooperation with other universities. The University, however, was said to want exclusive rights or nothing at all, so it is not really set up to deal with these cooperative research results. The Center has been at the forefront of generating issues that the University has to deal with, and a new one was said to arise about every two weeks; the administration does not enjoy this.

Overall Impacts

The impacts of the CBE on Montana State University are substantial, due in large part to the size and visibility of the ERC in such a small public institution, although not without continuing points of disagreement. In recent years, CBE's $4-5M annually in grants and contracts represented 8-10% of the University's total R&D. The Center forged new levels of cross-departmental collaboration within the College of Engineering, and between the College of Engineering and the College of Science. Faculty participation represented some 11 departments within the University, with students drawn from 13. Within the College of Science, the major participant was the microbiology department, but faculty and students were drawn from physics and chemistry as well. The net result of this extensive cross-university collaboration is perceived as having increased the University's receptivity to interdisciplinary research efforts, which were few and far between at the time the Center was established. Nevertheless, as with many of the other universities covered in this study, certain barrier and disincentives for cross-departmental collaboration remain, including issues around credit for research funding, ICR policies, and promotion and tenure criteria.

One area in which the Center's impacts are considered more deeply ingrained in the current University culture is the involvement of undergraduates in research. While a number of other influences on a national level are also leading to increased undergraduate involvement in research labs, at MSU the ERC was the first to actively promote such efforts and its visibility increased the desire of others to follow suit. The University has now created a new position, a Coordinator of Undergraduate Research, largely on the basis of the model provided by the ERC.

The ERC was also credited as one of the primary forces in the establishment by the University of an IPR Office to deal with patents and licenses. Much of the activity of the Office was said to originate with CBE, as well as a number of continuing unresolved issues. CBE activity is creating pressures for the University to codify some of its IPR policies.

In general, practically all ERC-like characteristics have taken somewhat of a hold on the MSU campus. The ERC provided a model for seeing faculty, graduate students, and undergraduates from different disciplines working side by side in the same laboratory. It provided a model for faculty to think in terms of multimillion-dollar interdisciplinary awards rather than hundred-thousand dollar individual PI grants. It said it is okay to "think big". While education has been and will remain the first among the University's goals of education, research and outreach, the ERC has created an incentive for the University to reexamine the balance between the three and the emphasis that should be placed on research.

NORTH CAROLINA STATE UNIVERSITY: ENGINEERING RESEARCH CENTER FOR ADVANCED ELECTRONIC MATERIALS PROCESSING

Background and Overview

North Carolina State University (NCSU) was founded in 1887 under the Morrill Act as the North Carolina College of Agriculture and Mechanic Arts. It became the North Carolina State College of Agriculture and Engineering in 1917, and was merged into the statewide University of North Carolina system in 1931. It was named a University in 1965 and is now the largest institution of higher learning in the state. The University is located in the state capital of Raleigh in the Research Triangle area, and has been developing a "Centennial Campus" adjacent to the University, intended as a "technopolis" that includes University, corporate, and government R&D facilities.

NCSU, with a 1999 total enrollment of about 28,000, is one of the mid-sized universities associated with the ERCs included in this study. It is also in the mid-range in its degree of emphasis on engineering, which represented 26% of the bachelors degrees and 21% of the doctoral degrees conferred by the University in 1999. The University's electrical and computer engineering, chemical engineering, mechanical engineering, and materials science and engineering departments, each of which involve some faculty participation in the ERC, were ranked 23rd, 25th, tied for 27th, and 22nd, respectively, in the 1993 NRC ratings of the effectiveness of research doctorate programs in engineering. *U.S. News* ranked NCSU's graduate school of engineering 28th among the 221 graduate engineering schools included in its 1999 survey, and 26th in its reputation among practicing engineers.

Industry has traditionally been a significant source of R&D funding for the University. From 1988 through 1998, the University consistently ranked between 4th and 10th in the nation in industrially funded R&D. In 1999, NCSU ranked 29th among all U.S. colleges and universities in terms of overall R&D, but 13th in funds from industry. The University has also shown a steady increase in license income over the past decade; AUTM figures indicate that it rose from $0.8M in 1991 to $7.8M in 1999. However, since the ERC patenting activity takes place primarily through the Semiconductor Research Corporation (see below), it is unlikely to have played much of a role in that increase.

The Advanced Electronics Material Processing (AEMP) ERC was established in 1988 as part of the third cohort of ERCs and was relocated to the University's new Centennial Campus two years later. The goal of the Center is to carry out research that will contribute to improved manufacturing capabilities in the semiconductor industry. According to the Center's 1998 *Year 10 Annual Report*, "When the center started in 1988 the materials and processes being explored were selected as appropriate for 250 nm [nanometer] devices. During the [previous] year the Center's goals have been redefined and modified somewhat to focus on processes and materials appropriate for 50 nm and beyond devices." (p.6)

The ERC was said to have emerged at a critical point in the University's development. During the 1970s and 80s, the University was trying to position itself as a key player in the Research Triangle. During the mid-80s, the University developed a plan for how it could integrate its research efforts with government and industry. It experienced rapid growth during the 1980s, but was reportedly not recognized as belonging to the research mainstream until it successfully competed for an ERC. The electrical and computer engineering department and the physics department were said now to be the departments on campus that receive the largest amounts of external research funding. The ERC was considered directly instrumental in that. The ERC was also credited with enabling the University to make its case with the state for the need for the Centennial Campus.

Other complementary forces spurring change in academic engineering research and education were going on at NCSU, as with other universities, simultaneously with the ERC. Even so, the ERC was said to have "broken barriers." A few centers began showing up on the campus during the 1980s, but they were small and not as far-reaching. The AEMP was more interdisciplinary, involved more students, particularly undergraduates, and had a higher degree of industry interaction. There are now over 20 centers in the College of Engineering, of which the ERC is still the largest. The AEMP was said to have provided the "guiding light" for these newer centers, providing a model for how it could be done.

Although some cross-departmental interaction was said to exist prior to the establishment of the Center, it was often on an *ad hoc* basis and on a much smaller scale. The Center has multi-investigator projects, with students and faculty drawn from a number of departments without regard to their departmental origins. Within the College of Engineering, it is reportedly now much more common to see cross-departmental collaboration. The Center was thought to have affected the College of Sciences as well. The involvement of the physics and statistics departments meant that some coordination between the two Deans was required.

Several administrators were of the opinion that the legacy of the ERC has now been set. The University now knows how to do something on this scale. It had a tremendous amount of visibility. It reportedly helped establish a culture in which one has to perform and deliver what was promised.

Engineered Systems

The Center focuses on materials development as applied to semiconductor devices. It does not actually develop the materials, but takes the research to the second level, the device level, in order to demonstrate its improved performance. According to Center personnel, the material and the process of making the material is what actually gets sold, but if the Center does not take the research far enough to actually show it in the device, industry would not be interested in it. Considerable interaction and different skills are required to make the transition into the device for a "feasibility demonstration," and it is in this sense that the Center is said to be operating at the "systems" level. Interviewees repeated, however, that work at the systems level stemmed more from necessity than from a strong interest on the part of Center participants in conducting these feasibility demonstrations.

Strategic Planning

Strategic planning has been important for the Center, but in recent years, the pressure to do such planning has come more from the need to increase its funding than from NSF. The National Technology Road Map for the Semiconductor Industry is updated every two years, and several people from the Center, including the Director, have been involved in that exercise. At the time of transition from ERC Program funding, the Center Director was asked to prepare a position paper for the Semiconductor Research Corporation on the Center's field of research, and he used this as an opportunity to reassess the strategic direction for the Center following the termination of ERC Program support. While strategic planning is now well ingrained in the Center's culture, it is unclear whether this has spread beyond the immediate participants in the ERC.

Interdisciplinarity

Participation across departments has been fairly stable since the Center's origin. Within the College of Engineering, faculty are primarily drawn from electrical engineering and materials science. A few faculty from mechanical engineering have been involved, and, from time to time, one or two faculty from chemical engineering. From the College of Sciences, two faculty members from the physics department and one from the statistics department have been involved with the Center since its earliest years.

The Center reports to the Dean of Engineering. There were said to be some differences in working with faculty from the College of Sciences compared to those from the College of Engineering. In particular, the transfer of funds between two separate deans reportedly was a somewhat complicated process. However, over time these differences were reduced by bringing in only those faculty who were committed to working in a collaborative mode. Faculty in the sciences were thought in general to prefer the single-investigator mode of operation, while engineers tended to prefer to work in teams; however, even within engineering, there are some individuals who prefer to work on their own.

All faculty associated with the Center are on tenure tracks within individual departments. Views on the Center's impact on departmental interaction and relations within the College of Engineering differed, depending on whether the perspective was from within the Center or without. The College has been an important source of resources for the Center over the years, providing equipment, matching funds, and space. From the perspective of faculty within the Center, this has been considered an important way of leveraging funds. However, for faculty not involved in the Center, the College's financial support for the Center has sometimes been considered excessive, in that it has committed resources that could have been devoted elsewhere. Some faculty outside of the Center reportedly have now formed their own centers in order to attempt to get similar financial support from the College.

Promotion and tenure criteria were said to create some problems in terms of interdisciplinary work, particularly at the promotion from assistant to associate professor stage. This is apparently not so much a bias against interdisciplinary work *per se* as a requirement that the faculty member produce evidence that he or she was the *leader* of the work in question. It was noted that this has always been the case, and still is. The promotion and tenure process was thought to have the potential of creating some difficulties for junior faculty associated with the Center, in that they needed to demonstrate that they could secure their own grants and generate their own research accomplishments. In addition, the nature of the publications produced by the Center investigators is different from the publications more typically associated with departmental research. As a result, the Center management advises its junior faculty not to rely totally on Center support but to secure their own research grants as well; since the faculty associated with the Center were generally considered above average in productivity, they were thought to have had little difficulty in doing so.

Indirect cost recovery was not an issue for the Center during its years of ERC Program funding. The ERC was never given any ICR return, because the University had made so many other financial commitments to the Center that it was felt it was not needed. The University's ICR policy is that 10% goes to the state, 5% goes to the Statewide University System general administration, and 85% comes directly to the NCSU Raleigh campus. Of the portion returned to the campus, 58% goes to the upper administration for infrastructure and 42% goes to the individual colleges, which in turn distribute a portion of that to individual departments. In general, it was considered easier to do cross-departmental research through the Center than through the departments because it did not raise any questions as to who should take the lead, or how the ICR should be allocated. The Center also often enabled faculty to use a special reduced overhead rate on certain grants. In addition, the Center's administrative and logistical support for proposals and grants was considered far better than what is available from individual departments.

Education

The primary impact of the Center on graduate students was thought to be the extensive involvement with industry that came about through association with the Center. Interviews with students indicated that most of the Center's students have greater interest in pursuing careers in industry than are students who work with single investigators. Graduate students spoke very highly of the exposure to industry researchers provided by the Center. Several commented that the very best professors they had seen – at any level – were those who had previous experience in industry.

The Center has developed a reputation that is now attracting M.A. students from elsewhere to come to NC State to finish their Ph.D.s. Undergraduate involvement in research was reportedly almost non-existent prior to the establishment of the Center. In some departments, especially those closely associated with the Center, undergraduate research is now the norm. Faculty reported hiring undergraduates to assist with their research – not in lieu of a graduate student but in addition to other students.

Students felt that the proximity they had in the Center's facility to faculty and students from diverse departments, was a definite plus. It created an environment in which people could learn from one another, recommend books, answer questions regarding laboratory procedures, etc. There was a lot of socializing that in turn led to new collaborations. Many especially enjoyed the annual reviews – both by NSF and by Sematech – as times when they could meet industry representatives and get a better perspective on what is important to firms. The ERC was also credited with attracting more students at the Ph.D. level. The electrical engineering department was said to have been producing about 5 to 10 Ph.D.s per years at the time the Center began operations; it is now producing on the order of 30 each year. The Center was credited with providing an enriching environment outside of the wall of the individual labs. There was reportedly a sense of family that developed around the Center. This family atmosphere was said to have developed into almost the equivalent of a new multidisciplinary department.

Undergraduate students liked the opportunity to advance from their initial standing as an extra set of hands in a laboratory to analyzing and interpreting data, to actually having their own project. They viewed the stipends they received as similar to a grant, and expressed a sense of responsibility to prepare presentations for the annual reviews, while also viewing these presentations as great learning experiences. Several commented that their ERC experience had been valuable in their applications for graduate school.

The Center has developed some new courses but not any new track or separate degree program. Because the Center has resulted in more faculty conducting research related to the semiconductors, this in turn has resulted in more courses. The Center has also developed specific courses for which it felt a need. It also developed a solid state minor at the graduate level that involves physics, electrical engineering, mechanical engineering, and materials science. Several people in the Center pushed for getting this minor established. The Center also runs a senior-level elective course for undergraduates, which has been effective in attracting students to become associated with the Center. However, the number of undergraduates signing up for the course has expanded to the point where the Center has had to limit enrollment in the course to 25 students because it is very expensive to get the supplies and wafers that are needed, as well as to make sure that support people are available in the lab to run the course.

The ERC was also said to have been an influence on the decision by the College of Sciences to develop a "Science House" to reach out to the public and private high schools in North Carolina. College administrators found that it was not efficient to have disparate K-12 outreach programs associated with the many center-type operations going on throughout the campus, and instead have tried to coalesce these activities in one overall mechanism. The Science House gets funding from NSF, the Eisenhower and Howard Hughes Foundations, and several pharmaceutical companies. The College of Sciences has made a deliberate effort to get a message out across campus that Science House is open to all; it is not intended to be "owned" solely by the College.

It was noted that while ERCs *per se* may not be the most significant impetus to the involvement of undergraduate students in research in U.S. colleges and universities in general, the ERC certainly was considered to be so on *this* campus. NCSU has established a undergraduate research symposium in which students involved in research grants and contracts throughout the campus report to one another on their work.

Industry Interaction

NCSU has always had relatively strong support from industry. The Centennial Campus now has about 25 partners on-site, about 15 of which are companies and the remainder government labs. ABB has its North American headquarters there; other firms share buildings. A requirement upon firms for renting space on that Campus is that there be some relationship with University researchers. A special intellectual property provision was established for companies that operate out of the Centennial Campus. Whereas the University would own any patent resulting from an industry representative working over several months on the main campus, any patents stemming from work on the Centennial Campus are owned jointly.

One of the most effective methods of technology transfer coming from the Center was thought to be the placement of graduates in industry. Industry is interested in commercializing some of the Center's technologies. Sematech has been helping the Center get its plasma deposition technology developed to the point that it can be moved into companies.

Most of the Center's patents have been patented through the Semiconductor Research Corporation (SRC). SRC pays all the costs associated with the process, and pays the Center $1,000 per patent disclosure, which saves the University costs of processing the patents. Little objection among faculty was said to exist to this policy, but it also offers little financial incentive for faculty to patent.

SRC has negotiated the right to any related patents that the University may hold when it processes a new patent application, as a form of insurance that there are no pre-existing patents rights that would prevent them from using the new patent. The SRC view on access to background technologies has been a thorny issue. The University tried to negotiate a compromise on this issue with SRC, but, in contrast to the reaction at other universities to similar confrontations, ultimately signed. Nevertheless, the University is not happy with the arrangement. There is a Power Semiconductor Center on campus that has generated about 100 patents, four of which are considered prime candidates for start-ups. While SRC supports research on campus only through the ERC, there is concern that its background technology agreement may affect all of these patents and potential spin-offs generated by the Power Semiconductor Center.

The ERC was thought not to have raised technology transfer issues on the campus as much as had other centers and activities that produce greater amounts of intellectual property. The University was not thrilled with the Center's decision to run its patents through SRC, but the Center felt it was better to get the technology out there on a pre-competitive basis and let industry decide whether to patent it or not. This is different than some other centers on campus, however, which sometimes have hundreds of patents, based on research funded primarily by large international companies.

Several administrators noted that 98% of the problems the University has with companies are IP related. The University's technology transfer office deals with about 50 centers/institutes/labs, designated as CILs under the North Carolina system. Of those, about 15 or so involve industry interaction or funding. Two years ago, the Office took over the management of all the research agreements associated with those 15 centers. While engineering tends to be high in the number of disclosures and patents issued, the University reportedly has not had a great deal of success in generating income from engineering patents; it did, however, have one successful spin-off company. While income is on the list of the technology transfer office's objectives, it has other interests as well. Their intent is to maximize the commercial potential. The "due diligence" part of the agreement (that the company will actually get the product out) is considered very important by the University. The impact on the local economy is also a consideration.

Overall Impacts

Successfully applying for and hosting an ERC was said to have put NCSU among the research mainstream. According to some administrators, AEMP's biggest influence was to provide a model for the over 20 newer centers in the College of Engineering. The ERC's high visibility also reportedly helped establish a culture in which one has "produce what one promises". Moreover, AEMP was said to have developed a "family" environment that has become almost the equivalent of a new multidisciplinary department. Within the College of Engineering, it is reportedly now much more common to see cross-departmental collaboration.

The atmosphere prevalent in the ERC served as a model that led to increased involvement of undergraduate students in research throughout the University. Before the Center was established, undergraduate research participation was said to be just about non-existent; now, undergraduate research is the norm in some departments, especially those most closely associated with the ERC. The ERC was also said to have been a factor in the College of Sciences' decision to establish a "Science House" for outreach to high schools, public and private, throughout the state of North Carolina.

There was no consensus on whether or not the Center has had any impact on departmental interaction and relations within the College of Engineering; views varied based on the interviewee's relationship to the Center. While the Center has devised some new courses, it has not developed any new track or separate degree program. However, reputation that the Center has developed over the years was said now to be attracting M.A. students from other universities to go to NC State to finish their Ph.D.s.

PURDUE UNIVERSITY: CENTER FOR COLLABORATIVE MANUFACTURING (CENTER FOR INTELLIGENT MANUFACTURING SYSTEMS)

Background and Overview

Purdue University was established as Indiana's land-grant university in 1869. Its 1999 total enrollment of approximately 39,000 students at the graduate and undergraduate levels combined rank it among the larger of the universities included in this study. Purdue's R&D expenditures totaled $226M in 1999, of which funds from industry accounted for close to 13%, placing it 38th among universities as a performer of total R&D but 16th as a performer of industrially funded R&D. Purdue is one of the few universities included in this study for which relatively significant shifts in its ranking in terms of industrially-funded R&D can be noted subsequent to establishment of the ERC. In the late 1980s, industrial funding accounted for about 9% of Purdue's total R&D compared to the 12-13% by the late 1990s. A portion of this increase is attributed to the ERC's impact in providing the opportunity for a fresh and new basis for relationships between faculty and industry. As a result of NSF's requirements, the ERC's relationship with industry became a more formal, rigorous and long-term than was the case with earlier industry-oriented centers.

With engineering constituting roughly a quarter of the bachelor and doctoral degrees conferred, Purdue is among the more heavily engineering-oriented of the public universities at which the earlier ERCs were based. Historically, Purdue's academic strengths have been in engineering and the life sciences. NRC effectiveness ratings place its departments of industrial, mechanical, and electrical engineering – those most centrally involved in the ERC – at 4th, 7th, and 10th, respectively. In recent years, *U.S. News* has ranked its overall graduate school of engineering as 9th in the country.

The institutional impacts of an NSF ERC upon Purdue University reflect the twinned effects of the current ERC, the Center for Collaborative Manufacturing (CCM), and its predecessor, the Center for Intelligent Manufacturing Systems (CIMS).[13] Purdue was one of the five universities to be awarded an ERC in NSF's first round of competitions in 1985. The transition from CIMS to CCM began during the ninth year of the first Center's development, when its leadership met with NSF representatives to consider the Center's future as it approached 11 years of support, the maximum then permitted under the ERC Program unless a Center successfully recompeted for a new ERC with a substantially different focus. From these discussions, Purdue representatives drew the conclusion that future NSF support required a new center engaged in a new research direction. They responded by proposing and successfully competing for a new ERC that emphasized collaborative manufacturing. Although some viewed this changed emphasis as a sort of "repackaging" of the Center, others regarded the changes as

[13] In this report the Center will generically be referred to as the ongoing CCM, unless the context is specific to the original CIMS.

quite significant. The transition was said to be particularly hard on students because the altered research foci meant that many of their degree projects had to be wrapped up quickly.

University interviewees credit the ERC with producing significant changes in the University's culture. These were concentrated in the School of Engineering, but also had some impact on the School of Science. More importantly, the ERC's impact extended to core University strategies, policies, and norms. These included promotion and tenure criteria, interdisciplinary graduate degree programs, cost-sharing policies, and the creation of center-based research laboratories.

The ERC's major cultural impacts upon Purdue were seen as occurring primarily during its first five years of existence as the CIMS, with these impacts institutionalized by the eighth year of NSF support. Part of the initial impact was attributed to the sheer size of the initial NSF award. At the time it was first announced, the NSF award for the ERC was reported to represent \$22M over an eleven-year period. At the time, this was the largest single award Purdue had ever received, although the total NSF funding under the award reportedly never quite reached the originally anticipated total. The sizeable initial impacts also are widely attributed to the strong leadership and commitment to the ERC of Purdue's Dean of Engineering at the time of the ERC proposal and during the initial years of its operation.

Purdue's success in securing an ERC also highlighted the potential research and resource gains from collaboration, and academic administrators were seen as following suit by increasing the attention they devoted to opportunities for collaborative interdisciplinary and intercollege initiatives. Prior to the establishment of the ERC, Purdue was notable as a place where the size of engineering departments made it difficult for either faculty or administrators to promote collaboration. Fostering of faculty interaction among various departments, to say nothing of across schools, was harder still. Purdue is now seen as heavily committed to cross-school, cross-campus initiatives: few policies, practices, or attitudes are held to constrain collaborative, interdisciplinary research or education. The ERC became the success story that promoted other University endeavors at collaborative, interdisciplinary centers. Purdue is now so open to the center mode of research that one department head has found it necessary to discourage young faculty from entrepreneurial impulses to start a center that may dilute their research efforts.

Engineered Systems

Assessment of the ERC's impact on a systems engineering perspective was confounded by the multiple and diffuse interpretations accorded this concept by respondents. To some, it is synonymous with the ERC's focus on collaborative manufacturing, which involves bringing people together so that the end result would be more than the sum of the parts or the work of a single investigator. Some skepticism about the meaningfulness of the term reportedly existed among faculty at the ERC's inception, but its operationalization became visible as research progressed. Faculty from materials science, chemical engineering, and mechanical engineering working together produced both a process and instruments that were highly valued by industrial sponsors. Other faculty remained unclear what the term meant, perhaps other than a broad view of engineering. ERC representatives did note that its ability to document a systems engineering focus was an issue during NSF site visits. It is not clear what influence the CCM, a more conceptually based center, is having on the evolution of an engineered systems approach.

Strategic Planning

The ERC reportedly affected strategic planning at three levels: within the ERC, within the School of Engineering, and at the wider level of the University.

Within the ERC, strategic planning began early. A research committee involving faculty from mechanical engineering, electrical engineering, industrial engineering, the Engineering Dean, and the ERC Director was quickly formed. Also formed was a committee of industrial representatives that reviewed the ERC's plans. Annually, the ERC worked with the Dean and department heads to encourage faculty to submit proposals to the ERC. The ERC then created four panels each comprised of approximately 10 representatives from faculty, industry, and the national laboratories to review the proposals. The Dean's intimate involvement in the ERC served to incorporate the ERC plan into the overall plan of the School of Engineering.

The ERC led to basic management changes in how the University related to industry. Interviewees noted that a mistake made by faculty prior to the ERC was to take industrial R&D funding and then to do their own projects without trying very hard to justify the results. With the establishment of the ERC, faculty had to learn that this attitude was not acceptable. The Center's method of awarding project funding guaranteed that ERC funding was not an entitlement. Advisory boards that involved multiparty commitments on the part of the University and firms were formed, and an external review process involving a volunteer panel of 7 to 10 faculty and industry experts was formed to review faculty proposals. The proposals were reviewed by the unpaid panels. "Weed out the mercenaries" was the objective, and this procedure worked well in establishing the ERC norms and expectations. The ERC retained the authority to renew projects, but had an announced strategy of seeking a 5-10% turnover in participating faculty. These practices provided assurances throughout the School of Engineering about the quality of the research being conducted through the ERC, the stability of funding for core faculty, and a sufficient level of turnover both to introduce new faculty and to avoid implications that its funding was an entitlement to a small group of insiders.

At the School level, strategic planning has become a routinized part of each department's activities. The School of Engineering's strategic plan features collaborative, interdisciplinary research, as do those of the individual departments. Almost every department in the School reports some form of collaboration with another department within the School and most have collaboration with at least one department in the School of Science.

At the University level, as described above, Purdue's strategic planning is weighted towards leveraging its research expertise in niche areas, such as environmental sciences, biotechnology, and computing, based on a center or institute model. In addition, the University has instituted a reinvestment program, funded by a central administration levy on salary savings, to nurture selected areas, with these areas being advanced via faculty proposals and then chosen by a committee of faculty and the Provost. Major weight in this selection process is given to the interdisciplinary and, ideally, inter-School character of the proposal.

Interdisciplinarity

The ERC is widely seen as having contributed significantly to the rise of a culture of interdisciplinary research at Purdue. Interviewees put major emphasis on changes in attitudes toward the feasibility and utility of interdisciplinarity, as well as the norms and institutional environments within which administrators, faculty, and academic units work together. Purdue is described by administrators and faculty as having had a tradition of separate powerful departments within the School of Engineering. These departments control their own budgets, are located in separate buildings, and have a history of being quite autonomous. They also are quite large, with some having 100 faculty or more. Department heads who had come to Purdue from other universities noted their surprise at the lack of cross-disciplinary research among engineering departments in areas such as manufacturing-related topics where they would have expected to find it. Coupled with intermittent support by School and department administrators, interviewees reported that these conditions were seen as hindering earlier efforts in the 1970s and early 1980s to promote large-scale interdisciplinary research centers related to manufacturing.

The CCM is seen as having produced the conditions needed for sustainable interdisciplinary research projects. As phrased by one academic official, the ERC proved an "existence theorem," namely that cross-faculty collaboration could be fostered, succeed, and generate desirable results. The Center involved faculty from several departments, including industrial engineering, mechanical engineering, and electrical engineering. The impacts also affected relationships in large departments, where faculty had tended to work individually in discrete subfields. For example, faculty in electrical and computer engineering are no longer limiting their with an interests to robotics, applied controls, or communications but are now described as working on common problems of manufacturing in ways they would not have without the existence of the ERC. Indeed, as described by the faculty involved, the level of interaction produced by the ERC was closer than at other research universities where they previously worked. One indicator of increased interdisciplinary interaction, according to interviewees, is that faculty now describe themselves in departmental materials and Web sites as working and teaching in multiple areas and disciplines.

The effects of the ERC have spread in part to the School of Science. As noted by the Dean of Science, although most of the ERC's impacts were felt within engineering, they also demonstrated the research potential of major collaborative interdisciplinary interactions to department heads and faculty in science. Science, with its strong culture of individual investigators, had relatively little cross-disciplinary or team based interactions in the past. This culture is seen as slowly changing, induced in part by the ERC, in part by other NSF programs. For example, the ERC's experience with the value of collaboration helped pave the way for submission by Purdue faculty of a number of proposals to NSF's 1998-99 Science and Technology Centers competition. The ERC experience also is seen as having helped guide the way for proposals to establish a Materials Research Science and Engineering Center (MRSEC) and a proposal for a new ERC that involves participation by faculty from the Schools of Engineering, Agriculture, Science, and Pharmacy. Not only did the ERC serve as a model for these proposals, but its director and administrative staff were called upon to provide advice and guidance by the faculty preparing the proposals.

Changes in promotion and tenure practices to better accommodate cross-disciplinary collaborative research are among the most widely cited impacts of the ERC. Respondents highlighted the careful attention given to promotion and tenure issues in the establishment of the ERC and the considerable advance effort made by School of Engineering administrators to reconcile collaborative, interdisciplinary activities based in the ERC with the School's promotion and tenure policies and expectations. Purdue's tenure system is described as faculty controlled; it consists of a departmental committee, a School committee (that includes department heads and faculty), and a University committee. At the time of the ERCs establishment in 1985, considerable concern was expressed about the promotion and tenure implications for young faculty who would participate in it. Given the historic emphasis on single investigator research, administrators took anticipatory actions to educate faculty about the School's new promotion and tenure expectations. Department heads met with the promotion and tenure committee to discuss the issue of collaborative research.

P&T committees became more careful in scrutinizing the contribution of each investigator. Although few departments have abandoned the concept of core (disciplinary-based) journal publications, collaboration has reportedly expanded the universe of journals in which faculty now publish. They no longer treat the IEEE imprimatur as sufficient: and other indicators, such as being first author and page numbers, no longer provide an adequate measure of the individual's contribution to team efforts and publications. Much emphasis was placed on how much more difficult it was to deal with the matter of publications.

Overall, rather than being an obstacle to promotion and tenure, participation in the ERC increasingly has come to be seen as a source of opportunities that enhance the research performance of individual faculty. It was reported that no faculty member involved in the ERC who reached the sixth year failed to be awarded tenure, although some may have been counseled out prior to that decision point.

The impact of the ERC on promotion and tenure policies in schools other than the School of Engineering is less evident, although developments in engineering clearly have the support of the central administration and other deans. A trend towards research collaboration is widely reported by administrators and faculty, including among the latter many who are not involved in ERC-based research. Still, certain disciplines were cited as having difficulty in accepting the collaborative research model in promotion and tenure assessments.

Centers permit Purdue to leverage its expertise and the strategy has made the University more competitive for federal research awards, which are increasingly requiring collaborative R&D teams. Competing for an ERC, for example, reportedly highlighted the need for the University to develop a cost-sharing policy that transcended that of individual Schools. Experience in negotiating the University's cost-sharing commitments to the ERC with NSF required Purdue to take a hard look at how it was financing cost-sharing and its management of its finances. This experience led to the development of a consistent University-wide cost-sharing strategy that was applied to competitions for other major federal awards.

Education

Students considered ERC support to be a highly prized "plum" as well as a career advantage. Tracing the impacts of the ERC on students, however, was complicated by the degree to which the ERC has become so deeply interwoven into University policies on the characteristics of engineering education that students were often not able to perceive differences between ERC and non-ERC experiences. ERC students viewed their educational and research experiences as highly normal – as one of them commented, "why would you do anything else?" They did acknowledge that the broader training of ERC students might have been a disadvantage in initial job placements, when prospective employers – industry or universities – were looking for traditionally trained, disciplinary-based graduates. However, none expressed a concern about current employment opportunities.

One aspect of the ERC experience highly valued by students was the flexibility it provided them to explore research being conducted by several faculty and in selecting their courses. Exposure to the research of several different faculty gave them opportunities to see a variety of projects before they started on their dissertation. The ERC's program also provided greater flexibility and new options (minors) for students in some departments, such as electrical and computer engineering and aerospace engineering, which have what were described as very structured curricula. The ERC-based minors increased the opportunities open to students to interview with firms they would otherwise not have contacted through the University's placement office. The ERC also built new cross-School academic programs. Faculty in communications, for example, report changing their courses to accommodate the inflow of engineering students, and arranged for ERC students to gain access to additional firms that served them well in thesis research.

Industry Interaction

The impact of the ERC on industry interaction must be viewed in the context of historic characteristics of Purdue's ties to industry. These ties have been quite close, reflecting Indiana's position as a major industrial state and the location in the West Lafayette area of plants of several major corporations. Purdue had a history of working with large companies, mainly in niche areas – chemistry was particularly involved with industry. Some of this interaction took place by means of the center mode of operation, largely funded by industrial contributions and dominated by principal investigator modes of research. Industry interaction in the earlier centers was dominated by relationships between individual faculty and corporate sponsors, and little synergy was seen to exist among research efforts of diverse faculty. Industry's interests were for applied R&D focusing on short-term objectives, whereas faculty, once they received funding from a center, were seen as showing little inclination to closely integrate their research with the needs of the companies providing the funding. In addition, Purdue's intellectual property rights policies were seen as inimical to long-term R&D partnerships.

The massive influx of federal research funds in the 1960s was seen as having led many faculty to look down on those faculty who were working with industry, seeing them as second-class citizens not fully engaged in academic pursuits. Consequently, one of the more interesting ways in which the ERC affected the University culture was in its "relegitimization" of involvement with industry. The ERC played some role in the increasing quantity of academic-industry interaction noted above, but it also enhanced its quality, legitimized such activity across the University, and sensitized the academic community to the issues involved, such as intellectual property rights and industry's ability both to support research in general and to pursue its proprietary interests in collaboration with the academic community. Industry was reported to have found the new ability to focus on interdisciplinary research an attractive evolution in its long-time relationship with the University. NSF support of the ERC was deemed "classy," and therefore elevated the standing of faculty working with industry. Centers are seen as providing for more effective interfaces with industry, and University officials note that they have received positive comments from industry about Purdue's ability to form interdisciplinary research groups. Overall, younger faculty are described as having grown up in a Purdue culture that values center-based modes of research and education; these faculty see career-building research opportunities in becoming involved with a center.

Hosting an ERC is widely held to have produced cultural changes in Purdue's relationships with industry in other ways. The ERC is credited with raising the quality standards of the University's industrial-sponsored R&D, of galvanizing new partnerships, and of familiarizing faculty with working with industry advisory committees. It also provided funding for more visionary and revolutionary research objectives than was possible under previous industrial support. As a result of the ERC's experiences, other centers also have reexamined their relationships with industrial sponsors, leading to a significant increase in total industrial support. The success of ERC faculty in getting industry funding without strings attached helped other faculty "catch religion" in seeking industrial R&D support. As they have developed these ties, they have grown accustomed to and experienced in marketing their ideas to firms.

Purdue's intellectual property rights policies have changed since the establishment of the ERC, but the ERC is not seen as having directly been the cause of these. The major change has been the strategy of seeking strategic partnerships based on long-term master R&D agreements with a select number of major firms. Such an arrangement reduces the amount of time needed to negotiate contracts, a step that had caused the University to lose contracts in the past. Until recently, however, the University would have been resistant to this type of arrangement. Purdue's master agreement with Caterpillar is an example of this type of contract. Typically, Caterpillar provided between $100,000 and $200,000 annually in support of R&D projects at Purdue. In 1998, the level of support increased to about $1.6 million annually.

Purdue's strategy for seeking intellectual property rights revenue from its research findings depends heavily on the field of invention. If the patent is in medical or biomedical classes, the University policy is to pursue license and royalty income; in electrical engineering, they are more willing to sign away rights for continued industry support. Firms in a particular line of industry are reported to have parallel preferences. Drug firms want tight patent restrictions, while firms in computing fields are reported as seeing patents as minor forms of intellectual property protection, instead wanting six months lead-time in seeing the research before it is published. In the case of the ERC, if a member found something of potential proprietary interest, the agreement was converted to a contract with IPR rights.

Overall Impacts

The impact of the ERC has been substantial at Purdue, initially concentrated in the School of Engineering and then spreading outward. The two most obvious areas of impact are in the demonstration of the effectiveness of collaborative research efforts, including the development of means for carrying out such work, and the legitimization and spread of university-industry links. The educational program in engineering was clearly strengthened, and the practice of developing interdisciplinary courses and curricula has spread throughout the University. However, it was reported that it was now harder to get projects started and that there was less collaborative work under the new Center than in earlier years, suggesting some erosion of its cohesiveness and funding base.

TEXAS A&M UNIVERSITY & UNIVERSITY OF TEXAS AT AUSTIN: OFFSHORE TECHNOLOGY RESEARCH CENTER

Background and Overview

The Offshore Technology Research Center (OTRC), established in 1988 as one of the fifth cohort of ERCs, is housed primarily on the campus of Texas A&M University (TAMU) in a large model basin simulation laboratory built by the Texas university system for the sole use of the Center. The Center is, however, a joint venture with the University of Texas at Austin (UTA), and operates under the auspices of the Texas Engineering Experiment Station (TEES), through which its NSF ERC funding was administered. The TAMU facility is used to simulate wind, wave, and current challenges to offshore structures. The Center's wave basin is said to be on par with only two others worldwide that are available for academic research, and the Center has developed crucial numerical modeling techniques that correct for the finite conditions of their basin. At UTA, the Center has office, library, and computational facilities in a building adjacent to the main campus in Austin. Work also takes place in individual laboratories of faculty participants at both universities. While several of the other ERCs included in this study involve collaborative efforts among more than one university, the OTRC involved a greater degree of interaction between the partners than was the case with most other two-campus operations. As a result, SRI’s site visit was evenly split between the two universities.

TAMU was founded as the Texas Agricultural and Mechanical University under the Morrill Act, in 1876. It was the state’s first public venture in higher education. Since then, the University has expanded its programs from agriculture and engineering to include a full range of disciplines in the liberal arts, business, education, medicine, and science. Reflecting this expanded role, the name of the institution was changed to Texas A&M University in 1963. It is one of the larger universities associated with the ERCs included in this study, with a 1999 enrollment of 43,000, of which about 18% were graduate students. The College of Engineering accounted for 13% of the bachelor’s degrees and 27% of the doctoral degrees conferred by the University in 1999.

UTA, now the flagship of Texas’ higher education system, was founded in 1883. It has a total of 49,000 students, of which graduate students represented about a fourth. The College of Engineering accounted for 10% of the bachelor’s degrees and 20% of the doctoral degrees conferred by the University in 1999.

The 1993 NRC ratings placed TAMU’s civil and mechanical engineering departments, those most heavily involved with the ERC, as tied for 23rd and as 26th, respectively. The same two departments at UTA were rated as 4th and tied for 13th. *U.S. News* ranked TAMU's and UTA's overall graduate engineering programs at 13th and 9th respectively, among the 221 programs surveyed in 1999. In the field of offshore technology, the universities were both said by on-site interviewees to be number 1 or number 2 in the country.

TAMU has generally ranked among the top ten U.S. colleges and universities in the nation in terms of R&D funding, with $402M in total R&D in 1999, when its ranking slipped to 11th for the first time. It has also consistently ranked among the top ten in terms of R&D funds from industry, which represented about 9% of its total R&D in 1999. The University of Texas shows a quite different pattern in R&D expenditures. It ranked 31st in the nation in total R&D in 1999, down from a high of 15th in 1990. Funds from industry have historically represented only about 2% of UTA's total R&D; however, beginning in 1996, industry has become a significantly greater source of funds, accounting for about 6% of the total in 1996 and rising to 15% of the total in 1999. Few interviewees, however, attributed this latter increase to the presence of the ERC.

Engineered Systems

The goal of the OTRC is to conduct interdisciplinary research and educate students in conjunction with industries involved in the development of offshore natural resources – primarily deep sea oil drilling platforms. This undertaking brings together engineers from many different disciplines: mechanical, aerospace, civil, and petroleum engineering, as well as the fields of composites and other materials, and oceanography and geophysics. Thus the research orientation of the OTRC is inherently interdisciplinary and systems oriented, but not without some tension.

Offshore exploration and recovery platforms represent huge and complex systems. The increasing depth of offshore operations proliferates and increases the challenges to the materials of which they are made, their structure, and environmental safety. The Center's research is divided into three thrust areas: fluid-structure interaction, materials/composites, and sea floor characterization. Unifying the three research thrusts is that all are ultimately applicable to the various types of structures being deployed or envisioned by industry. The industrial members, themselves, were said to be beginning to develop more of a systems view; three companies pointed out to the Center the potential applicability for the Center's research of an approach used by Boeing that entailed a complete design of the entire 777 model aircraft on computers before beginning the development of actual components.

When testing model structures in the basin, researchers were, in principle, dealing with such systems in miniature. However, each thrust involved in such tests was said to be primarily interested in its own agenda – structural stability, materials strength, non-linear wave mechanics, etc. Faculty reported that there was very little interaction between the different research thrusts. In that sense, the OTRC did not itself develop much of an engineered systems approach and therefore had little in this regard with which to influence the rest of the Colleges of Engineering or either of the universities involved at large.

Strategic Planning

The Center itself operated on the basis of a five-year plan, subject to annual revision in consultation with its Advisory Board. There originally were four thrust areas, but in 1992, these were consolidated into three in order to provide better coordination and more adequate funds to individual PIs. These three thrusts persisted through the period of NSF funding, but evolved to reflect the increasing depths at which industry sought to operate with deep-sea technology. In anticipation of the need to develop new plans for the post-NSF period, the Director retired at the end of 1996 and a new Director took over. The transition management team then began working on defining a new role for the Center. They developed a three-year strategic plan with special attention to insuring that the new initiatives and ongoing programs could be completed in that time frame. The plan also included an effort to secure a line item in the state budget and a new position in the Center to strengthen their ties to industry through an office located in Houston.

The OTRC is proud of the fact that it made several risky and controversial decisions in planning its research program, including working on "spar" floating structures and going into composite materials. It was noted, however, that they had not really begun to get into composite materials until 1993, at least partly because industry was slow to recognize its need for durable, lightweight materials for deep-water installations. At the time, it was a very controversial decision, but this is now a very promising field.

Interdisciplinarity

The interdisciplinary impact of the Center on the two institutions is probably greater at TAMU because the Center is located on the TAMU campus and provides a stronger focus of activities than its office facilities in Austin. UTA has less flexibility in its funding and is more influenced by a traditional disciplinary organization. Its efforts to move toward more interdisciplinary centers are not as great as some in the central administration desire, but are limited by available funding. For example, the University's ties to the semiconductor industry were not yielding the amount of support needed for an initiative to establish a Center for Telecommunications. TAMU was perceived as more flexible and pragmatic in its approach to centers, including being more oriented toward applied research and more accommodating to industry. The administration has become highly supportive of the development of new centers as part of an overall strategy to improve the University's academic reputation. The University has made a strong commitment to the OTRC, including five years of $250,000 transition funding to add to money coming from TEES, but is concerned that the character of their "crown jewel" and model of an interdisciplinary center will change with an increasing dependence on industry funds.

Some interviewees indicated that, prior to the Center, TAMU may not have been particularly receptive to interdisciplinary work, but this appeared to stem more from departmental concerns than administrative culture or barriers. While the two universities had different approaches to interdisciplinary work initially, in the years since the Center was established, both campuses have become quite hospitable to center-type and other interdisciplinary work. The OTRC was credited with helping to encourage this transition in a period in which research trends and funding sources were moving in this direction in any event, than something directly attributable to the Center.

The UTA administration has a set policy for reviewing research centers, while TAMU does not. Each center at UTA is visited and evaluated every four or five years. On the basis of this evaluation, the University funding is either increased or phased out. There is no precedent for evaluation at TAMU, but the University likes the OTRC and is working hard to ensure its continued existence, while exploring the establishment of other center-type activities.

The Center was said to have moved cooperative research to the inter-university level, a difficult undertaking given the geographic separation and historic rivalry of the two institutions. However, inter-university projects were reported to be just that: more likely to involve people from the same department at each school than the more interdisciplinary character of projects that were developed at one or another of the universities. This may change: new deans took over the Colleges of Engineering at both schools. In addition to being enthusiastic supporters of inter-university and interdisciplinary work, the two deans share a long-term friendship stemming from their days together in college. The other major characteristic of inter-university collaboration was data exchange. There has been outreach to other universities, including M.I.T., Stanford, the University of Houston, and others, when needed talent was available at neither of the host institutions.

The OTRC was formally guided by a Steering Committee that included the heads of all departments with faculty involved in the Center. The primary role of this Committee was to ensure that credit for work at the Center was properly factored into P&T decisions. Although the logistic problems of bringing this group together meant that it did not meet frequently, it evidently achieved its major goal. A recent Center Annual Report stated that there had not been a single case in which faculty involved in the OTRC research program had been denied a promotion,[14] which was consistent with on-site interviews.

Indirect cost recovery did not play much of a role in the Center's operations or interactions with departments. Basically, the Texas legislature funds the universities on the basis of class credit hours, and deducts ICR from the appropriation. As an alternative source of funds, the universities have the "Available Fund," based on income from oil derived from the university system's land holdings. These resources led the legislature to appropriate little for buildings, forcing the universities to borrow against the Fund's income to build. A separate and unmortgaged category of Fund monies is available for improving research, and that is now being partially given back to the faculty in a way that resembles ICR return policies at other universities.

Education

With the exception of the summer REU program, most of the Center's educational programs have been at the graduate level. Involvement of undergraduates in research has reportedly never been very strong in the College of Engineering on the TAMU campus, and the Center has continually struggled to get faculty to work with undergraduates. The TAMU administration, however, feels that undergraduate involvement in research is on the rise on campus, largely due to NSF programs that have promoted using undergraduates. Undergraduate involvement in research appears to be much more common at UT Austin. Students connected with the Center at Austin complained, however, of insufficient access to the TAMU PIs when they go there for NSF site visit reviews.

[14] Offshore Technology Research Center, *10th Annual Report and Renewal Proposal*, May 1988, Vol. 1, p. 55.

Initially, the OTRC's educational program was handicapped by the depressed state of the oil industry. Few jobs were available, and so it was difficult to attract students. With the industry's upturn during the 1990s, its thirst for students rapidly increased, exceeding the ability of the pipeline to match demand. Little difficulty existed in the late 1990s in attracting students at both the graduate and undergraduate level: in fact U.S. universities are unable to meet industry's needs. The Center's ability to train students with a clear understanding of the multidisciplinary character of offshore engineering is highly valued by industry, and graduates have no difficulty in finding jobs in industry. A number of graduate students interviewed came from abroad and hoped to return to jobs in their own country's oil industry. At the graduate and professional levels, the Center introduced a two-month summer offshore institute for graduate students and professional engineers who want to get acquainted with offshore technology.

At the TAMU facility, undergraduates were reported to lack skills needed to take on more than fairly simple laboratory tasks in the complex facility. At TAMU, one professor referred to engineering undergraduate involvement as lip service, saying undergraduates were skilled enough to take on only the most mundane laboratory tasks. It was agreed at both universities that those undergraduates involved with the Center were exposed to much more industry interaction and "real world" engineering than other students. In part, this followed from the use of industry representatives instructed undergraduate as well as graduate courses at TAMU. Contacts included OTRC-sponsored seminars and an annual Industry Workshop, as well as site visits to deep-sea structure construction facilities. Summer programs involved both UTA and TAMU students, as well as REU students from other schools. The Center also sponsored an ocean engineering degree's senior capstone course, which included undergraduates not directly involved with OTRC. The course was taught twice a week by engineers from a member firm. More changes in undergraduate curricula attributable to the Center appear to have taken place at TAMU than at UTA.

Industry Interaction

When the Center was established, available "deep sea" technology operated in depths up to 1,000 feet, with the goal of extending capabilities to 3,000. Over the years, this has increased so that projects can now be planned in depths around 5,000 feet and the new vision is to go as deep as 10,000. Interest in these depths has led to an industry initiative, "DeepStar," that parallels the Center's goals, although not through research *per se*. DeepStar links oil, testing, and supplier companies, as well as consulting firms and has formed close links with the OTRC. Certainly TAMU is perceived as being closer to industry in general, and the oil industry in particular, than is UTA (which has close ties with the semiconductor industry).

The financial base of the OTRC's industrial constituency is potentially enormous, embracing both oil exploration and oil producing companies. In 1998, OTRC lead a total of 35 industry members plus an affiliation by the U.S. Department of the Interior's Minerals Management Service (MMS). The MMS manages the allocation of offshore leases. Like the ERCs at Utah/Brigham Young and at Lehigh, the industry is considered to be relatively conservative in its approach to research; the boom and bust fluctuations in the price of oil have resulted in firm downsizing and outsourcing of their research. As the price of oil stabilized in the range of twenty-five dollars per barrel, deepwater exploration became increasingly attractive and has provided a strong motive to support the OTRC's work. The commitment of most Center participants has remained strong despite the corporate mergers and name changes that have occurred in the oil industry.

The Center's relationship to industry is oddly contradictory. While the industry was perceived both to be quite conservative in its research vision and to have irretrievably lost a great deal of its research capabilities, Center respondents noted that the research budgets of industry remained huge and outweighed anything that they could do in research areas that industry was really serious about. Moreover, industry was ahead of the OTRC in certain areas like corrosion, and Center hopes that they could catch up with industry in these areas proved futile.

Industry treats its research as proprietary. Center researchers found that industry would happily tell them when they were on the wrong track, but not when they were on target. Data provided to OTRC researchers by industry usually had to remain confidential, a hurdle for a collaborative research environment. Although OTRC did not have any unusual problems in the area of intellectual property rights, there was some friction. As public institutions, both UTA and TAMU are subject to state IPR guidelines. These guidelines were not acceptable to about 10% of the industry. Member complaints were voiced that industry's "we pay for it, we own it" attitude puts the University in a situation of subsidizing industry, because companies did not pay for the true costs associated with the research. Giving in to this pressure was considered to be a violation of the University's public responsibility.

Overall Impacts

In both participating universities, the OTRC provided a model for center-based interdisciplinary research in what was an increasingly favorable climate for such work. It also increased the interest and legitimacy of faculty working with industry. While it had an impact on educational programs and included some undergraduate activity – particularly through REU programs at both universities – this impact was limited by the specialized nature of its research focus. At least at TAMU, developments in undergraduate engineering education were largely attributable to external factors, such as TAMU's participation in an Engineering Education Coalition. OTRC fostered interdepartmental interaction through its management of its space on both campuses and was successful in gaining recognition for its participating faculty in promotion and tenure. However, the laboratories used at UTA were and will continue to be basically departmental facilities, while the basin model building at TAMU is a large and specialized facility in need of modernization to keep up with the field's demands. OTRC did little to develop or spread to other departments an engineered systems approach. Much of the Center's influence must be said to have been a facilitating and contributing factor in processes being encouraged by other developments in engineering research and education.

UNIVERSITY OF COLORADO AT BOULDER: OPTOELECTRONIC COMPUTING SYSTEMS CENTER

Background and Overview

The University of Colorado at Boulder (CU), established in 1876, is the main campus of the University of Colorado System, which also includes campuses in Colorado Springs and Denver, as well as a Medical School in Denver. With 1999 total undergraduate and graduate enrollments of about 29,000, it is one of the mid-sized publicly funded universities associated with the ERCs included in this study. Engineering represented 8% of the bachelor's degrees and 24% of the doctoral degrees conferred in 1999.

The Optoelectronic Computing Systems (OCS) Center was established in 1987 as part of the third cohort of ERCs.[15] While there were other centers in the University at the time the ERC was established, reportedly none was as large as the OCS eventually came to be. The ERC represented about $70M in funding for CU's College of Engineering over a ten-year period. The university system itself conducted about $320M in R&D in 1999 on all four campuses[16], of which about half was conducted by the Medical School, and most of the remainder by the Boulder campus. The ERC's annual expenditures of approximately $7M represented about 4% of the University's R&D total. However, it represented slightly above 20% of the College of Engineering's annual R&D expenditures of about $34M, and was by far the largest single research entity in the College – the next largest project having a research budget of about $2M annually.

OCS was heavily engineering oriented: of its total faculty/researcher complement of about 50, only 5 – 4 physicists and 1 chemist – were from outside the College of Engineering. Within engineering, most of the faculty associated with the Center are from the electrical and computer engineering department, with some from mechanical engineering. NRC 1993 effectiveness ratings ranked the University's electrical engineering program as 38th of 126 that were rated, and the mechanical engineering program as 60th of 110. The University's overall engineering program was ranked 30th among 221 that were rated by *U.S. News* in 1999.

The effort to put together the ERC proposal was said to have been a College-wide and University-wide effort. Originally, the Center reported to the Dean of Engineering Subsequently, a new Dean moved the Center's reporting channel to the chair of the electrical and computer engineering department (ECE). These organizational moves had important implications for the operations of the ERC, mainly related to the apportionment of ICR funds. In the original reporting arrangement, the ERC director had negotiated an agreement that all indirect cost recovery generated by the Center was to be returned directly to the Center. Under the revised arrangement, some of the ICR was retained at the departmental level rather than

[15] A portion of the OCS budget supported activities at Colorado State University, its partner institution in the ERC. However, most of the faculty, students and administrative structure associated with the Center are located at CU, which was therefore the primary focus of this study of institutional impacts.
[16] Data for the Boulder campus are not broken out separately in the NSF reported data.

being returned to the Center. This change contributed to adversarial relationships between the ERC and the department, and was seen by many as diluting the institutional impacts of the ERC.

Among the ERCs in this study, OCS is the singular case of a major change in research objective at the mid-point of its eleven years under the aegis of the NSF/ERC Program. The Center's original research objective was to achieve an increase of three orders of magnitude in the performance of computers by harnessing photons (i.e. optical computer) as opposed to electrons (i.e. electrical computer). This thrust led to development of the first optical computer. By 1993, however, this area was seen by the Center, industry, and academe as the wrong technological path: the objective of developing a technologically and economically competitive optoelectronic computer was seen as unfeasible, given continued improvements in microelectronics that reinforced that technology’s role as the dominant design. What proved to be of value from OCS’s research, however, was the development of underlying technologies that provide peripheral equipment to computers and other industrial end-users. Two new research thrusts were accordingly initiated: optical-electrical interconnect devices and optical signal and image processing. The Center’s research agenda and subsequent success in securing industrial and state government financial support for its research and educational activities now centered about the use of optoelectronics applications in computing systems. This revised research trajectory also led to closer attention to product development, the launching of spin-off firms, and better alignment with the state’s economic development objectives.

The ERC’s impacts on the University were described as subtle, at times amorphous changes – what one interviewee referred to as the “Zen-ness of ERC-ness” – that slowly spread throughout the campus. For example, senior University officials, while noting that multiple national influences led CU to initiate several changes that paralleled the ERC’s objectives, favorably commented on the ERC’s value as an exemplar. They saw it as a tangible demonstration that the programmatic and organizational changes they were pursuing were in fact feasible. Central administrators, in particular, saw themselves as more heedful than faculty and departments of the changes impacting on the resources, public standing, and structure of research universities and of the expectations of external constituencies that University research and education will contribute in some significant way to national and state objectives. To these administrators, centers, as exemplified by OCS, provided a useful organizational mechanism to achieve these broader institutional objectives. In the case of OCS, these were considered to include its contribution to educational innovation, interdisciplinarity, interaction with industry, and technology transfer. These contributions affected both the academic units most directly associated with OCS and others in the College of Engineering. They also enhanced the valuation accorded cross-disciplinary engineering research in tenure and promotion decisions throughout the University more broadly.

OCS was credited with helping produce changes towards a greater acceptance of an interdisciplinary and systems approach to research. The collaboration among physics, chemistry, and electrical and computer engineering was cited as placing engineering ahead of other colleges on the campus in achieving the degree of interdisciplinary collaboration being championed by the central administration. CU is perceived by interviewees as increasingly open to and flexible about the value of interdisciplinary, team-based research in its tenure and promotion practices, although these changes are reported to have occurred mainly in the substantive application of existing tenure criteria rather than in the formulation of new criteria. Another reported positive aspect of OCS was that it helped change the campus perception of the value of working with industry; it demonstrated that industry is interested in working with the universities, as well.

The former CU Dean of Engineering who was in office during the formative period of the ERC placed special emphasis on the ERC concept itself as a catalyst for institutional and cultural change. Voicing concerns about the characteristics of academic engineering research and education in the early 1980's, he noted that a need existed at that time for greater interdisciplinarity and a systems focus in engineering research. He reported pressing hard to convince faculty on the campus that engineering research was becoming too narrow, and that while it was focusing on interesting intellectual problems, it was giving inadequate attention to applications. However, funding support for changes in the direction of engineering research, was difficult to find. Universities had limited resources and role models; industry, while calling for these changes and bemoaning the traits of academic engineering, was not willing to put money into changing University cultures. Relatedly, CU's institutes, several of which had ties to federal mission agencies, were viewed on campus as models of good science as well as interdisciplinarity and problem-focused research, but their activities were directed primarily at fields of science, not engineering. The ERC provided a model in the College of Engineering of a combination of good engineering research with a focus on applications. For example, it focused on the miniaturization of optical experiments in physics rather than being content with an alternative research protocol that might have yielded the same scientific results, but which would have had little commercial value because the size of the equipment limited the application of the finding in commercial settings.

While ERC impacts on research achievements, institutional ranking, technology transfer, and intra-institutional cooperation were noted, most interviewees described the major institutional impacts of the ERC as lying in the areas of contributions to graduate and undergraduate education. Students were seen as getting a first-rate education in both basic sciences and applications-oriented engineering as a result of the presence of the ERC. Students learned to work in team-based projects and to interact with industry. The ERC was also seen as a powerful recruiting tool, attracting better students to CU.

A spill-over effect of the educational model created by the ERC was said to be the planned establishment by the University of a Discovery Learning Center (DLC) as an adjunct to its previously established Integrated Teaching and Learning Laboratory. The ERC was said to have been a partial motivation for the new DLC, in that it demonstrated that the linkage of undergraduates to the research process works. It was thus credited with buttressing the DLC's underlying concept that research is less a product and more a process of learning. The involvement of undergraduates in that process is seen as beneficial to students and faculty alike.

Engineered Systems

The Center's research thrusts are described as directed at "exploiting the synergy between electronics and optics for approaching problem domains that are difficult or impossible to solve with either all-optical or all-electronic processors." The end products of the Center's research are integrated devices that function seamlessly in an overall system – an emphasis, in other words, on systems compatibility. The systems approach of the Center was said to have begun to have a ripple effect on other departments (e.g., the mechanical engineering department was in the process of hiring an electrical engineer to do mechanics). The systems concept was said to force people to think across lines, to ask “What would be needed from me over here for what they are doing over there?”

The beneficial result of this systems approach, according to OCS, is that “materials researchers keep device researchers realistic in what can be built, while device researches provide feedback to materials researchers on the effectiveness of their materials and the importance of different parameters. Similar interaction occurs between systems designers and device researchers.” Faculty participating in OCS described several similar impacts upon research. They report becoming accustomed to working in different ways, to working with other departments, and to working with industry. One faculty member noted that after he had become part of OCS, his team’s work became very systems oriented, and his research began to take into account the constraints of other disciplines. For example, in developing packaging material for a product, his team understood that the material could not adversely affect the properties of the optics. The interaction was said to have helped define interesting research projects. Another example cited was the broadening of one ECE researcher’s approach: his involvement through OCS with a faculty member in chemistry led him to explore the use of organic photoconductors to drive photoelectronic devices, a technique used by chemists. He had originally been taking a different tack but once introduced to the technique, ended up hiring a chemistry postdoc to assist in his research. He observed how he and the postdoc had battled over terms, but in the end their collaboration had led to the redefinition of the technical problem.

The systems approach was also considered an important aspect of the Center’s educational mission, which was described as one of “educating students in the multiple disciplines of optoelectronic computing systems, thus creating new industries and a new work force for the 21st Century.” One impact of the Center was said to have been its development of a new optics curriculum, which involves a systems perspective.

Strategic Planning

The OCS reportedly benefited significantly from strategic planning. In 1993, when the Center was advised by faculty and NSF to give up their major research thrust of optical computing, the Center's willingness to address that advice strategically and frankly was thought to have allowed the Center to live on. OCS annual reports also note that Center faculty have played leadership roles on major University-wide committees, such as the Vice Chancellor’s Academic Planning Committee, which does the strategic planning for the University. OCS faculty, drawing on the Center’s experiences and their positions in these University-wide committees, are perceived as having had an impact on the strategic plans of the University.

Interdisciplinarity

The University of Colorado had a history of interdisciplinary research in its institutes and centers, some of which date back 50 years. However, very few of these institutes involved engineering. OCS is credited with bringing the spirit of interdisciplinarity into the College of

Engineering. The former Dean of Engineering reports that the research funding of the College increased from $3M to $34M during his tenure, and he attributes this growth in large part to the growth of interdisciplinary research efforts within the College of Engineering, of which the ERC was probably the most visible component.

About 60% of the interdisciplinary research in the College of Engineering is reportedly conducted through centers, although most of these are intra- rather than inter-college operations. The model of the individual investigator working with his own students was said to be in the minority within the College now. An interdisciplinary background is considered a plus in hiring decisions; so is the ability to work in teams, whereas ten years ago, one might have heard "this person is involved in research in a large group, but what is his unique individual contribution?"

CU was described as a place where it is becoming increasingly easy to do interdisciplinary work.. OCS is seen by administrators, center personnel and other faculty as serving as a role model for interdisciplinary and team-based research. Faculty who were not directly involved in OCS also saw positive spillover benefits from the increased interdisciplinarity and team-based projects fostered by the Center. One such faculty member observed that when she came to CU there were few collaborative projects. Seven years later, she was personally engaged in four collaborative projects.

The College of Arts and Sciences is reportedly now actively promoting interdisciplinary degree programs. The OCS, as noted previously, involves only five faculty in two departments outside the College of Engineering (physics and chemistry), but there were nevertheless thought to have been ripple effects on these departments. A faculty member in the physics department reported that the existence of OCS and its research thrusts had led his department to make optics a sub-specialty, hiring two additional optics physicists in addition to the one existing faculty member who specialized in the subject.

There is reportedly a growing consensus among CU's central administration of the need for greater breadth in interdisciplinarity in a graduate education, especially in programs offered at public universities. This view is attributed in part to increased pressures on CU, as with other public universities, for accountability – which has the effect of inducing increased attention to problem-focused, and hence interdisciplinary, programs of study. CU officials also observed that universities in Western states tend to be less tradition-bound than the established universities in the East in adopting new organizational arrangements.

The Center was said to be a major factor in changing promotion and tenure criteria to be more responsive to interdisciplinary and team-based research accomplishments. The Center Director and several Center faculty served on a committee formed to evaluate and revise these criteria. They had found it necessary to explain to faculties in the College of Arts and Sciences that publication practices of faculty in the College of Engineering tended to involve more multi-authored publications than in other colleges; this practice, however, applied to all faculty in Engineering, not necessarily only those participating in OCS. The perception was that faculty in other colleges were beginning to better understand these differences.

One current department chair reported that interdisciplinary research was now sufficiently ingrained in tenure and promotion policy to make a visible difference from the setting when he left the University to go elsewhere in 1984. The culture of giving credit only for single-author papers in promotion decisions has also reportedly been changing. But questions linger, such as what happens when there are eight or even ten authors of a paper, which is often the case with publications stemming from the Center's research?

Two issues surfaced surrounding department-Center interactions that were thought to have served as barriers to greater institutional impacts of the ERC at CU. First, several respondents highlighted the seeming disparity between the prestige and contribution to research and education that accrued to CU because it was a host institution for an ERC and the decline in the NRC ranking of the electrical and computer engineering department (ECE), within which the ERC was administratively housed and from which it drew the majority of its faculty. Between 1982 and 1993, ECE fell in these rankings from 36^{th} to 38^{th} in the effectiveness of research-doctorate programs and from 21^{st} to 37^{th} in faculty quality. Some of the faculty believe that this decline is in part the result of focusing of funds and faculty on OCS research areas. However, some were of the opinion that parts of the department aside from the OCS were not productive, which would account for the thriving of the OCS during the period of the rankings drop. In addition, there was some feeling that perhaps the department had not made use of the ERC as well as it should have.

Second, the apportionment of indirect cost recovery funds among units was a source of discord for many years. ERC personnel spoke unhappily about the practice of the former ECE chair of using ICR funds accruing from the Center's research to pay off a departmental debt rather than returning anything but a negligible amount to the Center. The Center's funding was around $7.5 million annually, and the rest of the department's was around $3.5 million, which made the ICR differential particularly significant.

Other collaborators in OCS also noted problems with indirect cost recovery. The head of the physics department observed that ICR recovery was a recurrent issue, and that prior to a change in the OCS Directorship, his department had received no indirect cost recovery funds from OCS. Relationships with the Center improved after the new Director changed this policy to return some funds to the department.

Education

OCS is reported to have had major positive impacts on graduate and undergraduate education at CU, both in the College of Engineering and in departments in other colleges. At the undergraduate level, the ERC was said to have been instrumental in bringing the linkage between education and research to a higher level on the campus. The science undergraduates associated with the Center, in particular, were said to have benefited from exposure to collaboration and the systems approach because they rarely get it at any other point in their studies.

Interviewees observed that CU's commitment to research experiences for undergraduates predates and is independent of OCS. The University participates in NSF's REU program, and has related programs for minority students. In physics, one-third of the departments' undergraduate students participate in an honors program that requires a thesis. Work on this thesis frequently is based on student participation in faculty research labs, underwritten by departmental funds.

The University administration noted that it has been working for the last five years to change the education it provides to undergraduate students. This objective was said to have been spurred, in part, by the national debate on this issue, and in part from the sense in the College of Engineering that students both need and want hands-on experience, increased communication skills, and greater concern for ethics and humanities. NSF's efforts to promote similar themes were also considered a factor in making the administration re-think its education-related initiatives.

Within this context, the University created an Integrated Teaching and Learning Laboratory (ITL). While the ITL was being developed, OCS was running its own educational programs that involved similar laboratory-type experiences for undergraduates. Cross-fertilization of ideas between the Center and the administration worked to the benefit of both the ITL and the Center. ITL's development was independent of the ERC, but the ERC helped it along. As noted previously, the University was in the process of establishing a Discovery Learning Center as an adjunct to the ITL at the time of the SRI interviews, and the Center's experience with undergraduate research teams was thought to have had more of a direct impact on the DLC than it had on the ITL, which was established at an earlier stage of the Center's existence.

At the graduate level, the perception was that the ERC's programs had also been very effective. The ERC was seen as leading the way in the development of multidisciplinary frameworks for getting a degree in one department but also working with other faculty. The Center reports that its goal of integrating new research results into departmental curricula has resulted in the addition of 41 new courses since its inception. For example, graduate students from the electrical and computer engineering department involved with the Center earn an optics certification at the end of their enrollment. In mechanical engineering, interdisciplinary approaches to the thesis were introduced that formerly were considered impossible. The Center has also introduced novel courses. For example, one ECE professor prepared a course on intellectual property that was eventually taught by an attorney. The course was open to all CU students, and even some faculty enrolled. As another example, students in a new management course developed by OCS but cross-listed with the Business School are developing new business plans.

The Center's educational programs were considered one of the principal attractions to industry. Faculty at the Center have heard from industry that they are not turning out the average "horribly narrow" undergraduates that come from other universities, which is viewed as a testament to the benefits of interdisciplinary teamwork. OCS students felt that the teamwork, the joint projects, the hands-on experience from the Center was going to make them much more prepared to work in industry. Students reported that the technology transfer orientation of OCS made life exciting. They learned how to write a lab report and patent disclosures. They also worked on projects that resulted in something that could be used. As contrasted with other centers on campus that emphasized papers and presentations, the clear message from the ERC was to get patents. Students view pursuing patents as a positive, challenging aspect of research. They noted that getting the disclosure would enhance the appeal to industry for further support of their work, more so than papers.

Among those highlighting the educational impacts of OCS were faculty who did not directly participate in the Center. One such faculty member noted that OCS had helped recruit bright graduate students to CU, some of whom enroll in her classes. Her undergraduate and graduate students interacted with ERC students during summer programs. She noted that her research interests were sufficiently different from those pursued in OCS that she did not attend its seminars, but she was appreciative of the increased level of seminar activity on the campus. She also spoke positively about the increased university-industry interaction fostered by OCS. Another faculty member likewise highlighted OCS's ability to attract bright graduate students to CU; in her view, it is a lot easier to recruit good graduate students if the University has a core faculty working in a cluster area, especially if their research is performed in well-equipped laboratories. She noted that she had been able to recruit ("steal") some of the Center's students to work in her lab.

Industry Interaction

The changes in OCS's research thrusts in 1993 are reported to have produced a commensurate change in industrial interest in its research. After the change, OCS found that smaller companies were interested in research on specific devices, as opposed to overall system work. This interest includes greater potential for funding, however, since industry interest in the optical computer thrust fell sharply before 1993. Many of the smaller companies interested in the Center's work are in fact spin-offs. The spin-off companies of the Center revolve around liquid crystalline devices and optical interconnects. The Center counts 10 companies as recent spin-offs.

In addition to spin-offs, the OCS offers incentives for the promotion of technology transfer. A privately endowed award, known as the Collins family award, is offered for student involvement in technology transfer; in addition the Colorado Business Program offers the Colorado Technology Transfer Award to the research teams that provide the best examples of Center technology transfer. Graduate students associated with the Center feel the Center is more focused on patenting than other centers and departments on campus. It was reported that patenting is seen as more prestigious at the Center than publishing. It was also reported that the dollars that patenting brings in are sought more than publishing's academic prestige.

Firms are perceived as more interested in coming to CU to see a cluster of faculty than a single investigator. The number of seminars in which industrial researchers participate has increased, as has industrial funding for these seminars. (OCS's seminars are open to all faculty.) One faculty member who is not directly involved in the Center commented on the high quality of the seminars, and also how they had helped her meet industrial representatives which proved useful in helping place students in jobs. OCS is also credited by the physics department as serving as the rallying point for the department's increased interaction with industry.

The Colorado Advanced Technology Institute (CATI), a state program, provided seed money for the Center to develop and manage programs that would foster the transfer of technology from the University to state-based firms. Any CATI member firm is automatically associated with the Center. A small company pays $5K, CATI matches that with $20K, and that $25K is the Center's minimum membership fee. Once a company becomes a member of the Center, the Center commits to doing a research project for it; this brings representatives of local companies into the University looking for a professor to do a research project. In this way, the firms get to know what the Center is doing.

In 1993, the University of Colorado Board of Regents set up a technology transfer office to handle intellectual property for the four campuses within the system. Initially this office was under the Vice President for Academic Research at the University of Colorado/Boulder, but in 1996 it was made a 501c(3) non-profit organization called the University Technology Corporation (UTC). By 1998, UTC was dealing with 118 invention disclosures. In 1997, UTC filed 77 patent applications, but of these, about half were provisional filings. (Provisional patents cost $75 each and are typically used by university technology licensing offices to "buy time" for a year)

The ERC reportedly has had a major role in the activities of UTC. The ERC was estimated to be among the top three sources of patent disclosures and the top five sources of patent filings. It was also among the top sources of patent holdings, with the former ERC Director herself holding 15 to 20 patents and several other ERC faculty also major players. The ERC, however, was said not as yet to be among the top ten sources of income generation from patents, although it is generating income. The ERC is also generating fees from two new spin-off companies, although it was considered too early as yet to generate licenses.

The President of UTC expects the ERC to be among the top 10 in the system in royalty generation in five years or so. He also sees the Center as a role model for research. Older centers generally tended to grant non-exclusive royalty-free licenses or rights of first refusal to their industrial members, thinking this was the only incentive that would get them to pay the membership fees. The OCS, however, on the advise of its Industrial Advisory Board, decided to grant only exclusive licenses, which are preferred by the UTC and the University administration. The UTC is trying to get other CU institutes and centers to adopt the policy of exclusive licenses, but is encountering significant resistance to this as yet.

Overall Impacts

The OCS appears to have played a role in cultural change CU in each of the broad areas of ERC Program objectives. Most of these changes were described as subtle, beginning with the departments most directly involved in the Center and slowly spreading more broadly throughout the College of Engineering and the campus in general. In terms of interdisciplinary team-based research, these changes included an increase in such work in the College of Engineering; a growing consensus on the part of the administration of the need to encourage and foster such research in other parts of the University; and a greater acceptance of the value of such work in tenure and promotion decisions. In terms of interaction with industry, the Center purportedly heightened the awareness on campus of the value of such interaction and raised the stature accorded patenting to a par with publishing in certain departments with which it was most closely affiliated. As a side note, in 1999, the former Director of the OCS Center became the Dean of Engineering at Duke University – a tribute partly to the value Duke placed on her ERC experience and to her extensive involvements with industry in that position.

The greatest impact of the Center was generally seen by faculty and administrators alike to be in the area of graduate and undergraduate education. The Center was said to have served as a model for students working in interdisciplinary teams. While the University's efforts to provide research experiences for undergraduates developed somewhat in parallel to the ERC's educational programs, the model provided by the Center was said to have raised this commitment to new levels. The Center appears to have played a direct role in the decision by the University to establish a Discovery Learning Center.

UNIVERSITY OF MARYLAND: INSTITUTE FOR SYSTEMS RESEARCH

Background and Overview

The University of Maryland at College Park (Maryland) is a public research university, the flagship campus of the University of Maryland System and the original 1862 land grant institution in Maryland. Maryland is the only public Research I institution in the state. With total 1999 R&D expenditures of about $250M, the University ranked 32nd among all U.S. colleges and universities, down from a high rank of 19th and 20th in the 1991-93 period, although up from those years about 20% in absolute terms. Funds from industry accounted for only about 1% of the University's total R&D in 1998 and 1999, down from an average in the 8-9% range throughout the late 1980s and early 1990s and the lowest percentage of any of the universities included in this study with the exception of Columbia. The University had a total 1999 enrollment of about 33,000 students, of which graduate enrollment accounted for about a fourth. The College of Engineering accounted for 9% of bachelor's degrees and 17% of doctoral degrees conferred by the University in 1999.

Maryland's doctoral program in electrical engineering, the department from which the vast majority of the ERC's faculty are drawn, was ranked 18.5th of 126 programs in the 1993 NRC effectiveness ratings. Its programs in chemical and mechanical engineering, the other two departments reflected in the ERC's faculty make-up, ranked 45th out of 90 and 39.5th out of 110, respectively. Maryland's College of Engineering is one of the few associated with the ERCs in this study to show considerable improvement in its rankings in *U.S. News* in the period for which data are available, rising from 44th in 1992 to 17th in 1998 and 1999, but down from its rank of 13th in 1997.

The Center for Systems Research (CSR), one of the first five ERCs awarded in 1985, was renamed the Institute for Systems Research (ISR) in 1988 when the state granted some line-item funding for the Center. The Center represented a significant increase in research funding at the University, coming at a time of substantial recession-induced austerity. Stress on the state and the University budgets at the time of CSR's establishment had required sharp cuts in state funds. However, soon after the establishment of the Center, the University of Maryland at College Park was legislatively designated in 1988 as the "Flagship Institution" of Maryland's higher education system. The flagship status has made the College Park campus a priority in state funding plans, with some of the "flagship funds" being provided for two staff lines at the ISR.

In terms of the cultural impact of an ERC, the ISR case combines a number of somewhat unusual circumstances:

- the University had a tradition of establishing centers and institutes (N.B.: not CSR);
- the Center embodied NSF's vision of an engineered systems approach in its very name, although developing conceptual content for the term "systems" proved difficult;

- the Center's initial Director was able to imbed the ISR in the state's budget as a line-item of financial support, providing an unusual core of steady funding for the post-NSF era;

- the Center was viewed internally as a major achievement for a then-second-tier research university, providing a morale boost and developing into an example of excellence to be emulated.

The University is described as having a history of creating centers and permanent institutes, such as the University of Maryland Institute for Advanced Computer Studies (UMIACS) and the Institute for Physical Sciences. Such institutes have helped in recruiting distinguished faculty to enhance both the department of their field and the University in general. Consequently, the ISR's distinctiveness did not derive from its status as a University research center, but in its approach to interdisciplinary and collaborative center-based research, its emphasis on links to industry, and its approach to education. These were seen as traits derived specifically from NSF requirements for an Engineering Research Center. Many of the other centers or institutes on campus are the creatures of single departments, and no other University institute was seen as having the sort of focused research program of the ISR.

The ISR represented one of the University's first efforts to advance its research reputation by "competing with the big boys." It has become a major focus of cross-departmental, interdisciplinary research at Maryland. At the time of the NSF call for ERC proposals, the departments of electrical engineering and computer sciences had each planned to submit separate ERC proposals, but University administrators mandated that these be merged – an act that was reported to represent a University-wide message that departmental parochialism would not to be tolerated. The ISR has become a highly visible entity, and the infrastructure developed during its years of NSF funding has provided a solid base for faculty seeking to pursue cooperative and interdisciplinary research efforts. The ISR is widely credited with having demonstrated the feasibility of large-scale, interdisciplinary research: it became the model for other interdisciplinary centers and programs, several of which have received major awards from NSF and other federal and industrial sponsors. In addition to the development of new "centers" within the ISR as new funds become available, the pre-existing Institute UMIACS, which also enjoys continuing funding in the state budget, has been conjoined with the ISR.

During its period of NSF funding, ISR established a reputation for administrative efficiency and organizational capability that has provided agility in pursuing new opportunities for cross-disciplinary research of the type that, according to University officials, is where an increasing number of funding opportunities lie. It thus became the organizational unit to which the then Dean of Engineering (now Vice President for Research), looked for placement of new interdisciplinary programs.

Engineered Systems

Although it would seem that the name of the ISR alone would ensure a "systems" approach, the development of this outlook was an extended effort, in which NSF's definition and the Center's approach were often in conflict. The Center perceived itself as being rooted in approaches to control and problem-solving derived from the thinking of Norbert Weiner on "cybernetics" and R.E. Kalman's computer-implemented aerospace applications. When the Center was founded in 1985, "control design was not at all integrated with other elements of design as an interactive, iterative process." ISR research thrusts were directed at bringing together methods from computer science with control, communications, and software design tools in the process of making systems engineering a broad-based science. It continues to claim coverage of a broad spectrum from fundamental research in these areas to their application in industry, moving the field toward greater emphasis on formal modeling.

However, coming up with a consistent, agreed-upon definition of what constituted systems engineering was a recurrent and thorny issue between the Center and NSF. The "systems perspective" which ISR participants associated with NSF's intent for the ERC Program seemed to combine a vertical integration that ran from basic science to the marketing of an application with a horizontal perspective that involved the cross-disciplinary integration of relevant research domains. NSF was seen as defining systems in terms of applications of engineering research to specific topics, whereas ISR wanted to highlight the methodological research that was at the core of their program. Although the Center's efforts resulted in winning awards from DARPA and firms for their methodological expertise, they had difficulty in convincing NSF that what they were doing fit the ERC Program definition. Indeed, some relief was expressed by participating faculty that the ending of NSF core support for ISR removed pressures in having to claim that all research clusters were engaged in systems engineering.

The perceived ambiguities and ambivalence extended to student perceptions. The University offers an ISR-administered M.S. degree in systems engineering, but not a Ph.D.-level program, *per se*. In the employment market, systems engineering is seen as a recognizable industrial specialty, but is not yet viewed as a recognizable academic field.

Strategic Planning

The first Director of the Center began with an objective at placing the ISR on a firm, long-term financial footing. Contrary to the NSF model, in which industry becomes the major source of self-sustaining funds for the ERC, the Director began two years after the establishment of the ISR to seek state funds. Provision of such support for earlier established centers on campus provided a precedent, and he was able to achieve line-item status for the ISR in the state budget. Achieving line-item status provided stable funding and showcased its prominence in the University. (Several other centers have since taken the same tack subsequently with varying success.) The process in Maryland is unusual, because the Governor presents a budget and the Legislature can only delete items. There is thus a rush to get into the Governor's budget, and ISR's favored position is seen as secure absent any very serious reason for its removal.

Strategic vision and strategic planning were seen as keys to ISR's success. Based on NSF's requirements for an ERC, ISR planned its research before it did it. This planning gave both coherence and direction to its work. Some of these traits were thought to have begun to dissipate following the termination of NSF core funding of the ERC. However, a continuing culture of cooperation across academic units has continued to benefit both ISR and participating departments. The current constructive fluidity of intercollege relationships is seen as an offshoot of the ERC model. Engineering picked up on the success of the ERC and used it elsewhere in the College's plans. ISR is a lure that strengthens departmental recruiting efforts. Flexible joint appointments between ISR and departments provided a constant renewal of faculty strengths within ISR and also served to strengthen departmental activities. Consequently, ISR has become a model for the University's strategy of establishing centers of excellence, particularly in areas related to information technology.

Interdisciplinarity

ISR used ERC funds as an inducement to build teams of faculty to work on collaborative projects. Large-scale collaborative work was described as an "unnatural activity" for many faculty, and the NSF funds were viewed as an incentive to overcome this view and work together. Administrative and financial hurdles also represented barriers to collaborative work. There were problems in arranging for shared funding of postdocs and in adhering to industrially imposed schedules of project meetings and project milestones in the University setting. At the same time, NSF ERC funding enabled ISR to invest in basic research in systems engineering that was difficult to fund otherwise because the projects crossed disciplines. Consequently, the University has achieved major successes in fostering cooperation between the College of Engineering and the College of Computer Science, Mathematics, and Physical Sciences (hereinafter College of Science), and has used this collaboration to foster closer ties within information technology firms in Maryland and, in turn, to secure state funds for new technology initiatives.

The University's support of centers and institutes has come to reflect a generalized commitment to interdisciplinary research, which several ISR participants attributed to the ERC as part of an overall ambitious endeavor to change the University's infrastructure to foster interdisciplinarity. While the goal of interdisciplinarity is widely preached at the University, academic units are still seen as continuing to erect barriers to its implementation. There was tension over the path of submitting proposals through institutes unless faculty from other departments were involved. This practice has been changed so that faculty are now free to choose the units that administer their proposals and funding. Still, some departments are seen as disliking faculty submitting proposals through institutes because of the lack of "credit" they receive in college and University performance reporting forms.

Like collaboration, interdisciplinarity was seen as a learning experience. At ISR's inception, the concept of interdisciplinary research was only loosely defined, and the selection of some of the Center's research areas was reported by some to have probably reflected a degree of naivete. They were making a good-faith effort to conduct cross-disciplinary research, but in some areas the approach did not seem to make sense to prospective participants. Time was required for faculty to learn when interdisciplinarity made sense and when it did not. Now, when it is appropriate, faculty can put projects together quickly: they have worked together and developed a common technical vernacular to deal with these situations.

Departments, at least initially – and still today to some extent, were seen as not quite knowing how to react when faculty pursued a research interest that moved outside of traditional disciplinary lines. Departments in the College of Engineering were seen as increasingly receptive to interdisciplinary work, whereas some departments in the College of Science were described as having a narrower orientation.

Some faculty noted there was a negative aspect of ISR's use of joint appointments because it established two bosses. At times faculty did not know which boss to listen to – department head or Center Director. Moreover, not all faculty within departments engaged in interdisciplinary research had access to ISR's resources, and at times believed that their efforts to secure individual investigator awards were adversely affected because the University had plowed all its funds into ISR. There was concern about the ways in which the ISR resulted in a form of "second-class citizenship" among faculty. The flexibility and added financial stability that the state funds provide to the Center remain part of the ongoing tensions between the Center's interdisciplinary work and departments as organizational units.

Collaborative, interdisciplinary research is now seen as a hallmark of ISR. The fact that the state line item funding does not fund research itself, but term-defined joint faculty appointments, is a major factor in sustaining this. The arrangement, however, cuts two ways. Faculty who have preferred to work alone, or are otherwise regarded as unproductive in the interdisciplinary setting, have had their appointments in ISR terminated. This can represent a serious problem to departments in adjusting their teaching loads. An ISR joint appointment, whether of a new hire or existing faculty, cuts in half the salary costs to the department, but necessitates coverage of the appointee's "buy-out." The reverse occurs if the ISR appointment is not renewed: the department must now fund the full salary of the usually tenured faculty member – and may have a commitment to someone hired to cover his teaching load.

Mixed assessments were offered about the impact of ISR's approach on other units in the University. Some faculty suggested that the interdisciplinary approach was an inevitable development and thus tended to limit or minimize their assessment of ISR's discrete impacts. Others noted that ISR's interdisciplinary approach contrasted with that of other University institutes (such as the Institute for Physical Sciences, which was described as being based on the single PI model), and had done much to foster a shift in the culture in using institutes as an organizational framework for interdisciplinary efforts. Still, at least in the College of Engineering, ISR's leadership in fostering interdisciplinarity was sufficiently evident that it was described as having been requested to take on leadership for nearly all cross-disciplinary activities on campus. One example of this expanded role is the "Gemstone" undergraduate program (described below).

In the case of graduate students, concerns were occasionally expressed about the difficulties of publishing interdisciplinary research. Some students were concerned that participation in ISR meant that they were neither fish nor fowl in both the job market and the publication domain. While other students were much more inclined to express an appreciation of their ERC participation as better preparing them to work in industry, the number of students concerned about their potential future in academia due to the interdisciplinary background they had received from the ERC was in distinct contrast to most of the other universities where interviews were held.

Education

The ISR's major impact on campus was viewed by some as its contribution to education, particularly to undergraduate education. ISR established fellowships, enabled students to gain practical experiences in working with industry, and provided new opportunities for undergraduates from across the campus to participate in research. While ISR is directly credited only for initiating the M.S. degree in systems engineering, it is seen as having had indirect impacts, too. Plans to develop a cross-disciplinary masters degree in technology management were viewed as building on ISR's educational accomplishments.

A highly significant educational innovation developed under the leadership of the former Dean of Engineering (now Vice President for Research) was an undergraduate honors program called "Project Gemstone." This project was partly inspired by the Center's mode of team effort, as well as by courses developed through the University's participation in an NSF Engineering Education Coalition that put emphasis on teaming and early design projects in the engineering curriculum. Incoming freshmen are specifically recruited into the program and assigned to teams that work together throughout their undergraduate career. The teams cross all disciplines and colleges – not just engineering. The program has been very successful, attracting increasing numbers of top-ranked freshmen. The Dean turned to ISR as the appropriate unit in the University to administer this interdisciplinary program. Other new interdisciplinary programs have been assigned to the Institute, whether or not they have been generated from the Institute's own research efforts and proposals.

Mixed assessments are offered about the distinctive contribution of ISR to interdisciplinary graduate education. Perhaps with the M.S. in systems engineering degree in mind, some faculty described ISR as a model for interdisciplinary degree programs. Others reflected the view that curricula were evolving in that direction in response to general influences on the content of engineering education, with ISR essentially reinforcing these trends.

However, the culture of students working together in interdisciplinary projects was seen as a new, permanent feature of graduate education, one that was reinforced by assigning students from different departments to share a single office in the ISR's building. Most students reported widespread valuable and "illuminating" participation in interdisciplinary, team-based projects as a result of their involvement with ISR. Association with ISR also facilitated their interaction with firms. Others saw less positive effects due to industrially funded research leading faculty advisors to direct students to projects that did not mesh well with the student's academic goals. Students' concerns about the "marketability" of interdisciplinary experience have already been noted.

ISR is widely credited with helping the College of Engineering attract high-quality graduate students, as well as for its operation of an effective REU program as part of the ERC.

ISR faculty also have encouraged students to set up interdisciplinary projects. They also report enjoying increased opportunities to participate in thesis-related research of students in different departments. Competition between ISR and departments does continue to exist, however, especially due to the problem of handling departmental teaching needs.

ISR faculty report that students who participate in ISR projects experience considerably more interaction with students from different disciplines than those who work in departmental labs. There was concern, however, that, while the ending of NSF support of ISR would not affect the total number of graduate research assistants in engineering, they might now be assigned in totally different ways – most likely departmental and PI fiefdoms. This would indicate that a culture of student involvement in cross-disciplinary research teams is not yet common in this University.

Industry Interaction

Interviewees described the College of Engineering's interaction with industry as dramatically different than it had been in 1985. Prior to the Center's inception, interaction with industry was said to be practically nonexistent. Establishment of ISR prodded the administration and the faculty to address the issue. The ability of the University to develop ties with industry was seen as constrained by its geographical location. Its proximity to Washington was seen as inevitably leading to greater interaction with and reliance on government agencies than with industry. Even the Engineering College was seen as tending to train students for employment with federal agencies, not industry.

ISR was said to have spread industry interaction throughout Engineering. ISR's Industrial Affiliates Program provided for three classes of membership: ISR Center/Consortium Member, Partner, and Sustaining Partner. It quickly received substantial support from major firms, such as Westinghouse and Martin-Marietta (the latter now absorbed into Lockheed Martin). Most other major firms that joined were based in Maryland. Lockheed-Martin is one of ISR's major supporters, and the original Center Director currently holds a Lockheed endowed chair. Close relationships also existed with Northrop Grumman, which provided over $200,000 in support annually for a number of years. This support is particularly valuable because it is apportioned between project-based research and support for ISR's generic research program. Several observers noted, however, that during its period of NSF funding, ISR had done little with smaller firms.

Industry initially bought off on the "systems" approach undertaken by ISR because it encompassed considerations of economics and risk in processes of technical design. However, industrial representatives are now seen as increasing their pressure on ISR to focus more on applications employing the years of NSF-funded basic research as a foundation.

The ISR was said to have created pressures upon the University to start to come to grips with intellectual property rights, an ongoing process. A major issue was reported to be the University's preference to issue exclusive licenses, believing that this was the right strategy to find the "pot of gold." University technology transfer officers appear to believe in a more "balanced" IPR strategy. Noting that the likelihood of substantial revenues from most patents is slim, they suggest that non-exclusive licenses may be a more productive strategy, especially for programs that involve industry consortia.

Overall Impacts

ISR's situation has had a significant impact on the University, at least in part because it was bolstered by some of the unusual factors noted early in this case. It was helped by the strong support of both College of Engineering and other central administrators. It began as a significant morale booster during a time of major financial stringency in a University that has since become an increasingly ambitious academic institution. Its influence began with creating incentives for faculty in the Engineering College in particular, but also in the College of Computer Science, Math, and Physical Sciences to work together and learn collaborative and interdisciplinary modes of research.

Its accomplishments are generally admired within both the academic and industrial communities. It has served as a role model within the University as a center of excellence and a model for development of the types of collaborative research that increasingly represent both funding opportunities and cutting edge areas of research. The ISR ethos extends well beyond the Center and the building in which it is housed. It has crossed College boundaries in attracting faculty participants and been imitated in the development of research foci within the University.

The degree to which this impact can be termed "cultural" must be conditioned by questions regarding other influences on the state and the University, and, more particularly on fields involved in the ISR. The University of Maryland is certainly a very different institution today than when the ERC was established in 1985. It is a major and upwardly mobile research University that is seen as an important key to its state's economic future. However, several other factors besides hosting an ERC have influenced this transformation. Although some of these encourage interdisciplinary work, there remains a strong departmentally based culture.

ADDITIONAL ERCs: A BRIEF EXAMINATION

This section provides a brief discussion of 7 additional ERCs that were not the subject of site visits conducted as part of this study. The descriptions are based on site visit interviews conducted as part of an earlier, somewhat related study and review of the Centers' annual reports.

Carnegie Mellon University
Engineering Design Research Center

The Engineering Design Research Center (EDRC) was Carnegie Mellon University's (CMU) first NSF ERC, established among the second cohort in 1986. The second ERC, in Data Storage Systems (DSSC), was established three years later in 1989. As described in the more detailed case study of DSSC, Carnegie Mellon was an unusually hospitable host for ERCs, having explicitly developed a long-term strategy that encouraged interdisciplinary work and faculty collaboration in order to establish a niche position for a relatively small institution. CMU also had a long-term commitment to working with industry, and had adhered to the original engineered systems outlook that had faded during the 1960s and 1970s at many universities. The cultural impact of ERCs on CMU is therefore hard to discern, given that the University culture already bore the stamp of many of the ideas underlying NSF's ERC Program. However, both ERCs represented a more formal embodiment and focused funding of interdisciplinary research, and the EDRC's influence was affected by both its earlier inception and the character of its research. The EDRC was focused on the topic of design generally, although its systems outlook led to the development of various artifactual outputs, such as wearable computers. This was epitomized by a four-month course developed and taught by the Center, in which students started with a blank piece of paper and ended up with a prototype artifact. By contrast, the DSSC was developed around the more hardware-oriented objective of improving particular engineered artifacts – data storage systems.

The EDRC was able to build on an already existing Design Research Center that developed about the ideas of Herbert Simon. While the Center drew participation by faculty from all seven colleges of the University and about twice as many departments, it had difficulty developing sources of outside funding for interdisciplinary work. In a period in which few sources funded interdisciplinary work, the funding that they did get generated went to individual departments, making the Center a very loose confederation where faculty came to collaborate. The EDRC essentially influenced the existing Center by moving its existing research interests to include additional activities, especially in education, and providing the intellectual focus and funding that had not materialized for the Design Research Center.

The Center has had an important impact on the way courses are designed at CMU. It demonstrated that while interdisciplinary teaching was harder to do than interdisciplinary research, it was possible not only to do it, but to carry it down to the freshman level. The EDRC helped break down barriers between departments and to encourage the development of joint courses. It injected a more hands-on practical approach as a major objective of curricular reform. In addition to a freshman design course, an interdisciplinary semester-long course on building the next generation of wearable computers drew attention to both the Center and to CMU as a multidisciplinary institution. Industry lined up to participate in the course, which gave students an opportunity to make on-site assessments of a firm's needs.

CMU was always open to interaction with industry, and both ERCs developed substantial industrial membership. The EDRC's highly multidisciplinary character made faculty participants realize that they could not really expect to bring all of the interested firms from different sectors together. The result was the organization of a number of consortia, some of which worked better than others. One on rapid prototyping, for example, broke down because each member wanted its own individual product. Some of the members have fallen away and there has been less willingness on the part of companies that helped fund the basic agenda of the Center since the end of NSF funding.

The Center continues to exist as one unit in a broader institute, the Institute for Complex Engineered Systems (ICES), which has a similar set of goals but a broader intellectual mandate than the EDRC. ICES, with a multi-year start-up commitment from the University, absorbed the infrastructure of the EDRC and took over the contiguous space that had been allocated to the Center. The infrastructure now supports not only the EDRC, but five other laboratories addressing themes such as tissue engineering and advanced infrastructure systems, as well as cross-laboratory activities in education and an Interaction Design Studio. ICES successfully joined with the Lehigh ERC to gain funding from the Pennsylvania Infrastructure Technology Alliance (PITA) to conduct research on bridge design and maintenance. EDRC's research funding has grown since its establishment in 1997, primarily based on federal sources. It also has sustained a program of industrial sponsors.

The EDRC has thus survived, as much because it was placed in a hospitable university culture as for any other reason. It clearly had an impact in moving this culture along in several dimensions, particularly curriculum reform, that were being encouraged by other programs and national trends, reinforced by the presence of its sister ERC on campus.

Columbia University
Center for Telecommunications Research

Columbia University is the fifth oldest institution of higher learning in the United States, founded in 1754 under royal charter as Kings College and changed to Columbia College after the Revolution. It adopted its present name of Columbia University in the City of New York in 1896, following an administrative consolidation of a number of loosely affiliated units. Today's School of Engineering and Applied Science has its roots in the mining school established in 1864.

Columbia's graduate programs dominate its enrollment, with over 13,000 students in 1999 compared to less than 8,000 undergraduates. Columbia is less oriented towards engineering than many of the other universities associated with the ERCs included in this study; in 1999, engineering comprised 15% of the bachelors degrees and 8% of the doctoral degrees conferred by the University.

Columbia is a major research University, and, with the exception of two years, its R&D expenditures have grown steadily between the late 1980s and 1999, when they totaled nearly $280M. In 1999, it ranked 26th in the nation, having dropped from 19th in 1988 in a fairly steady decline in rank despite its growing total R&D expenditures. The proportion funded by industry was only 0.9%, about one-third of what industry's share was in the late 1980s to mid-1990s, and the lowest of any ERC host institution included in this study. In terms of license income, however, the University has shown a steady growth, with a 45% increase from 1998 to 1999 when it received $95.8M from this source.

The NRC's 1993 effectiveness ratings ranked Columbia's electrical engineering program 12th and its materials science 26.5th among all graduate programs rated. The University's overall graduate engineering program was ranked 31st in the nation by *U.S. News* in 1999; however, it was 64th in its reputation ranking by practicing engineers.

The Center for Telecommunications Research (CTR) was established in 1985 in the first cohort of ERCs. The Columbia ERC enjoyed contiguous office and laboratory space in one of the University's newer facilities, a 1992 building housing the Center for Engineering and Physical Science Research. During the years of its NSF funding, the Center was said to have embodied all of the characteristics promoted by the ERC Program. However, as the NSF support ceased, the "ERC culture" began to be stripped away. Although the Center hoped to recompete for a new center with more of a "new media" focus, it was not successful, and the Center no longer exists as an administrative unit at Columbia. Two of the Center's thrust areas, however, continue to pursue interdisciplinary research in the Center's laboratory facilities.

Faculty and administrators indicated that Columbia might be an *extreme* example of a campus with a strong disciplinary focus. Tenure decisions are based on accomplishments within one's department, which tends to create risk aversion to conducting work in a center environment. While the ERC itself was interdisciplinary, it was not strongly so. Even so, there were several examples cited of faculty who did not gain tenure in the electrical and mechanical engineering departments because their industrially related research focus within the CTR was considered "unacademic."

Most of the research at Columbia was said to be based on grants to individuals; it is not a Center-intensive place. There was reportedly very little incentive for faculty to run their grants and contracts through a center, because they have greater control of their own project funding by running them through their departments. They prefer to run their grants through their departments. It was considered unlikely that even collaborating faculty from the computer science and electrical engineering departments – those most closely associated with the ERC – would run funding they had received from DARPA, for example, through the CTR.

At the time of the SRI interviews, the Provost and Vice Provost of the University were both committed to launching new interdisciplinary research initiatives on the campus. This is exemplified by the University's taking on the management of the Biosphere 2 facility in Arizona and the conversion of the earth sciences laboratory that pioneered in plate tectonics research into the interdisciplinary Lamont-Doherty Earth Observatory. In addition, the Provost rarely uses his discretionary funds to support an activity that involves only a single department.

Nevertheless, the Center's cultural impact on Columbia was quite limited. Its approach of developing individual industrially funded projects left the various thrusts interdisciplinary, but isolated. It tended to produce good technology without always generating good applications. Meanwhile, the hegemony of the departmental disciplinary base remains uneroded in the P&T process, which does not usually reward such efforts. Fostering interdisciplinary work is now primarily dependent on a combination of push from the Provost's office, with some specific funding initiatives, and the initiative of a handful of individual faculty.

Duke University
Center for Emerging Cardiovascular Technologies

What is now known as Duke University traces its roots back to 1838, with the founding of a Methodist Church-affiliated school that became Trinity College in 1859. In 1924, the Duke family established an endowment for Duke University, which subsumed Trinity as its undergraduate college for men. Duke is now a major multi-faceted Research I University, home of the Duke Medical Center and a Divinity School that is emblematic of its continuing affiliation with the Methodist Church.

Undergraduate programs are divided between the Trinity College of Arts and Sciences and the Pratt School of Engineering, the latter having been established in 1939. In 1999, Duke's total enrollment was about 12,000, 46% of which was at the graduate level. Engineering degrees awarded in that year represented about 12% of the baccalaureates and 14% of the Ph.D.s conferred by the University. The core department in the ERC, biomedical engineering, was ranked 12th in the NRC's 1993 effectiveness ratings. *U.S. News* placed Duke's graduate engineering program as 33rd in its overall rankings, identical to its reputation rank by practicing engineers.

Duke's research intensiveness has increased greatly during the past decade, showing a steady pattern of growth. With total 1999 R&D expenditures of about $350M, the University has moved from a rank of 42nd in 1987 to 17th in 1999 among all U.S. colleges and universities. Duke's growth in R&D support from industry has been especially remarkable. In absolute terms, the University rose from a national rank of 24th in 1987 to 1st in 1999. At 35% in 1999, the share of industrially funded R&D to total institutional R&D at Duke was also proportionately the highest of any of the universities hosting the ERCs included in this study. The percentage of its total R&D funds it received from industry was twice as high as MIT, ranked 2nd in terms of absolute dollars from this source. The University's income from licenses peaked in the mid-1990s, although its number of patents issued and licenses executed was higher at the end of the decade.

The Center for Emerging Cardiovascular Technologies was established in 1989 as part of the fourth cohort of ERCs. The impacts of this ERC on the University culture appear to have been substantial. Prior to the establishment of the ERC, the University was highly oriented toward basic research and single investigator awards. The cultural changes attributed to the ERC range from those most immediately apparent in the departments directly associated with the ERC to more subtle changes reflected campus-wide. A shift is reported from individual principal investigator research to goal-oriented, team-based research programs that embody an engineering systems approach. This shift is widely held to be a direct impact of the ERC on those departments most directly involved. The ERC is perceived as having impacted the College of Engineering more broadly in terms of increased interaction with industry, both in research and teaching. In terms of other colleges within the University, the ERC is credited with providing a model that has led to increased acceptance of interdisciplinary research and increased involvement of undergraduates in research. The research building which houses the Center was considered a major factor in fostering such interdisciplinary work. The building, which was designed with the objective of allowing undergraduate education and graduate research, collaboration with industry, and interaction among disciplines to occur in the space, houses elements of the Schools of Medicine, Engineering, Environment, and Arts and Sciences. Throughout the building's five-year construction process, the ERC was used as an example of what it was intended to accomplish: interdisciplinary research, education, collaboration, and outreach.

The University was said to have been committed to undergraduate involvement in research and to increased student diversity prior to the ERC, but the Center was said to have enhanced this commitment. Administrators indicated that this commitment, especially the component focusing heavily on handicapped students, will continue independently of the ERC. The Center developed a novel arrangement wherein successive classes of graduate students serve as mentors for undergraduates, which is also being emulated in other parts of the University. The ERC was also credited with enhancing Duke's curriculum and degree programs, a legacy that is likely to continue no matter what the ultimate fate of the Center itself in the post NSF-ERC period.

The ERC was credited with serving as a mechanism to evaluate, modify, and initiate policies to enhance the University's long-term relationships with industry. Patents, conflicts of interest, and other industrial collaboration issues have been on the national agenda for some time. While the ERC did not drive the University's policy-making related to IPR and technology transfer, it was always a major consideration in the development of these policies.

Lehigh University
Center for Advanced Technology for Large Structural Systems

A $500,000 endowment from Asa Packer, founder of the Lehigh Valley Railroad, was the initiative that founded Lehigh University in 1865. A private, non-denominational university, it began admitting women to graduate programs as early as 1916, but did not become co-educational until 1971. The University has always been strongly oriented toward science and engineering and aimed at combining scientific and classical education. Its founding "schools" were in the fields of civil engineering, mechanical engineering, mining and metallurgy, and analytical chemistry, as well as one in general literature. Today, the University describes its goal as providing "a liberal and scientific education for practical service," and boasts of its ability "to cross academic disciplines to provide an integrated learning experience."

Lehigh is the smallest of the host institutions for ERCs in this study, with a total enrollment of just over 6,000 in 1999. Slightly over one-third of this was at the graduate level.

Engineering represented 29% of the bachelor degrees and 47% of the Ph.D.s conferred by the University in 1999. Of the institutions associated with the ERCs included in this study, only MIT has a higher proportion of engineering graduates at either level. Of the departments most involved in Lehigh's ERC, its civil, industrial, and mechanical engineering and its materials science departments were ranked 18th, 14th, 23rd, and 16th in effectiveness of research-doctorate programs in the NRC 1993 ratings. *U.S. News* ranked its graduate engineering program overall as 40th in the nation, but 29th in its reputation among practicing engineers.

Lehigh's R&D expenditures are relatively modest among institutions that host ERCs, at about $28M in 1999, ranking Lehigh 123rd among the nation's colleges and universities. However, the share of total R&D support the University derives from industry is notable, comprising 24% of its 1999 total, second only to Duke University in the percentage of R&D attributable to this source. In all but one year since 1994, the University's license income has increased, although the number of licenses executed, patents applied for, and patents granted remains relatively modest.

The Advanced Technology for Large Structural Systems (ATLSS) ERC was one of the second cohort, established in 1986. ATLSS was advantaged by Lehigh's acquisition of Bethlehem Steel's research campus, located on a mountaintop above the University's main campus. There, a large facility, named the Multidirectional Experimental Laboratory, was incorporated into existing buildings. The laboratory made three-dimensional testing of large-scale structures possible, ranging from building components to bridges and ship structures.

Like that of several other ERCs included in this study, ATLSS's industry constituency is a conservative one that invests little in R&D, and the Center was not very successful in convincing industrial membership about the virtues of long-term research. Other countries are viewed as being far more receptive to research and risk-taking in the field of structures. Center participants had international contacts, such as Nippon Steel, but such firms were not within the Center's membership. The Center largely tailored its program to appeal to regional companies. Center students who were hired by the industry were largely at the masters degree level: little demand for Ph.D.s is held to exist among firms in the building industry.

The University's overall culture is, in principle, highly receptive to the goals of NSF's ERC Program. Interaction with industry is common. In addition, University administrators noted that the small size of the University tends to facilitate cross-departmental interaction. However, the cultural influences of the ERC on the University were considered negligible, if any. The University provided a hospitable environment for interdisciplinary research, but the narrow focus of the Center and the culture of its industrial constituency meant that it had little influence on the University's culture, while it had a limited capability to draw on supportive aspects of the surrounding institutional culture. It is an exception to the pattern in which Centers in relatively small universities often appear to have had more of an impact than in large institutions. ATLSS itself will almost certainly survive as an entity within Lehigh because its large facility guarantees continuing industry interest in its capabilities. Its character will change, however, losing most of what little ERC desiderata it achieved under the years of ERC Program support.

Ohio State University
Center For Net Shape Manufacturing

Ohio State University (OSU) was established by the state legislature in 1870 as the Ohio Agricultural and Mechanical College to take advantage of the Land-Grant Act of 1862. After a bitter dispute over the scope of the institution's curriculum was narrowly resolved by the Board of Trustees in favor of a "broad gauge" approach that was to include arts and letters as well as agriculture and mechanical sciences, the institution's name was changed to The Ohio State University in 1878. With a 1999 total enrollment of 48,000 students on its main campus, including 12,000 graduate students, it is the largest institution in Ohio's historically pluralistic system of higher education. It is also one of the largest universities associated with the ERCs included in this study. Engineering represented about 8% of the bachelors degrees and 13% of the doctoral degrees conferred by the University in 1999. *U.S. News* ranked the OSU graduate engineering program as 22nd overall and 18th in its reputation with practicing engineers among the 221 U.S. programs rated in 1999. In 1993 NRC rankings, the three OSU departments most relevant to the ERC were ranked 24th for mechanical engineering, 12th for industrial engineering, and 19th for materials science.

OSU's R&D expenditures almost doubled between 1989 and 1999, rising in a steady pattern of growth that climbed from about $170M in 1989 to over $300M in the latter year. The result was that the University's ranking in total R&D spending among all universities and colleges rose from 26th in 1987 to 19th in 1999. Industry funding of $52M accounted for 16% of OSU's total R&D funding, placing the University's overall rank as 5th in absolute dollars from this source. Income from licenses has been erratic, and was only $1.6M in 1999.

The Center for Net Shape Manufacturing (NSM) was established in 1986, among the second cohort of ERCs, and it continues to operate today using the same name under its founding Director. However, during its years of NSF funding, the Center did not develop strong ties with faculty in many departments. Although participating faculty saw the ERC as a source of funds, they did not develop a stake in the Center itself and remained more closely tied to their home departments than to the Center itself. This was partly due to a very strong emphasis on industrial interaction in the Center with which faculty had difficulty conforming. After initially providing fairly generous amounts of funding to various departments, the Center administration's dissatisfaction with faculty participants' failure to develop more satisfactory relationships with the ERC's industrial constituency resulted in less funding for departmental faculty and more for Center activities themselves. There were consequently fewer departmental degree candidates participating in the Center, and the Center began to take in visiting scholars from abroad, who assumed much of the burden of operating the Center. At least initially, these foreign scholars were not formally enrolled as students in the University, further distancing the Center from individual departments. This meant that the NSM had a limited role in education and curriculum reform. Its educational role has become limited to the support of five or six graduate students at the masters degree level and an NSF-funded effort to develop instructional CD-ROMs.

As a consequence of these institutional dynamics, the ERC did not develop a strong interdisciplinary character, nor much of an engineered systems outlook. It is relatively isolated from the faculty and had little impact on the University culture. Support from the University is limited to the Center's continued control over its laboratories.

The Center's continued existence is largely due to its close ties to industry. These, too, represented an obstacle to faculty involvement. When the Center faced the transition from NSF funding, its industry members, which strongly influenced the operation of the ERC through the Director, had no interest in seeing any major changes in the Center's *modus operandi* nor its research agenda. This meant that most faculty had no incentive to assist in the recompetition effort, which was unsuccessful, nor in other ways of assisting in the transition. The effort to develop a culture of cooperative interaction with industry remained confined to the ERC itself and did not influence the broader University culture.

University of Illinois
Center for Compound Semiconductor Microelectronics

Chartered in 1867 as Illinois' land grant university, the University of Illinois at Urbana-Champaign has a budget of over $1B per year and has consistently ranked among the top twenty research universities in the country. Although it dropped from 10th in 1987 to 20th in 1995, it was ranked 16th in R&D expenditures in 1999. The University's R&D support from industry has not been consistent. It rose from $11.4M in 1987 to a peak of $24.4M in 1991, roughly the midpoint (5th year) of NSF's support of its ERC. At that time industry was providing 10% of the University's total R&D funding, but since then steadily dropped to only less than 4%, less than the 6% provided in 1987, the year after the establishment of the ERC. Similarly, the University's license income peaked at $4.4M in 1997 and had dropped to $2.9M by 1999.

Illinois' total enrollment in 1999 was close to 39,000 students, of which roughly 10,000, or more than 25%, were graduate students. Engineering represented 16% of bachelor's degrees and 23% doctoral degrees conferred by the University during the same year. The College of Engineering's graduate program is one of the best rated in the country, ranked as 6th overall by *U.S. News* in 1999. The NRC ranked the three departments most deeply involved in the Center, chemical engineering, electrical engineering, and materials science as highly effective – 6th, 3rd, and 7th respectively – in its 1993 ratings.

The Center for Compound Semiconductor Microelectronics (CCSM) was one of the second cohort of ERC awards in 1986. A key feature of the original proposal was a new Microelectronics Laboratory building, funded by the state of Illinois, with a substantial area devoted to clean room facilities. The state has also provided substantial funds for the operation of the Laboratory over the years, and provided $16M to equip the laboratory for a new biotechnology thrust being developed in the post NSF funding era.

The University had a history of being receptive to interdisciplinary centers and had been home to an NSF Materials Science Research Center as well as the Beckman Institute, which provides quarters for several interdisciplinary programs. The University was described as having a history of "big team" operations, and there is a recognition of the need to co-locate researchers around particular themes. Illinois currently hosts a substantial number of interdisciplinary efforts in center or institute form.

Despite this culture, the Center was said to have gotten off to a rough start because of insufficient cooperation among the participating faculty, requiring a reorganization and new management. The NSF review process emphasized the need to develop a cooperative culture, not just within the University, but among its industrial partners. Some of the faculty had difficulty adapting to the collaborative character of the research and dropped out of the Center. In the long run, faculty participation became heavily dominated by the Department of Electrical and Computer Engineering. This helped in the development of an interdisciplinary approach because the Department was, itself, intrinsically interdisciplinary. This may be the reason that, while interdisciplinary approaches were reported to be spreading on campus, few observers specifically attributed this to the ERC. In general, the Center was credited with helping to change the culture of the University and reinforced the national trend toward more cooperative research. CCSM's impact was seen as occurring in conjunction with multiple factors affecting research and education and a pattern of overall change throughout the country.

Working in the semiconductor field meant that the Center had an agile and demanding industrial constituency. It was also a field in which corporate sponsors had large research budgets in spite of downsizing and were often able to accomplish much in a shorter time than was possible in a university environment. The semiconductor industry was characterized as one of the most demanding in terms of IPR, which raised issues concerning continued investment in the Center. However, the Center was reported to have nourished connections with industry that would never have developed without it, at least partly because of a strong Technical Advisory Committee.

The CCSM was reported to have had a significant influence on the educational culture of the College of Engineering, particularly in initiating a senior design project. A great deal of undergraduate involvement was reported to have taken place in the Center. An undergraduate summer intern program was carried out by CCSM, and a number of new courses were developed by junior faculty. The Center's students were highly regarded by industry and were said to represent the closest tie between CCSM and industry.

University of Minnesota
Center for Interfacial Engineering

The University of Minnesota was originally founded as a preparatory school in the Minnesota Territory and reorganized in 1869, thereby taking advantage of the Morrill Act and becoming Minnesota's land-grant university. There are four University campuses located around the state with varying degrees of program breadth, while the main "Twin Cities" campus is located on several sites in Minneapolis and St. Paul. The University is organized so that its "Institute of Technology" constitutes what is, in effect, a college of engineering and science. The University had total enrollment of about 45,000 students in 1999, of which roughly 13,000 were graduate students. Engineering represented 13% of the baccalaureate degrees and 14% of the doctoral degrees conferred by the University in 1999.

Although the University's overall R&D expenditures increased quite steadily since the late 1980s to a total of about $370M in 1999, its rank among all U.S. colleges and universities decreased from 7th in 1987 to 15th in 1999 (after a brief jump to 3rd in 1991). The amount coming from industry held fairly constant at about $24M since 1994, after showing a steady increase until that year. Thus, the University's national rank in terms of industrial R&D funds fell from a high of 8th in 1994 to 18th in 1999. Income from licenses was $6.3M in 1999.

The University's chemical engineering research-doctorate program, central to the CIE's research, was ranked number 1 in effectiveness in both the 1982 and 1993 NRC ratings. Among other participating departments, the University's biomedical engineering program ranked 17th, electrical engineering 18½th, and materials science 14th in 1993. Overall, *US News* rankings placed the University's graduate engineering program as 23rd in the nation in 1999, with its reputation among practicing engineers 19th.

The Center for Interfacial Engineering (CIE), established with the fourth cohort of Centers in 1989, was described as being unusual among ERCs in that "*its distinguishing mission and vision are to establish interfacial engineering as an intellectually coherent field and apply it to a wide range of technological areas*," as opposed to most ERC efforts to bring various disciplines and their principles to bear on a single technological area.[17] There was a strong interdisciplinary culture at the University before the Center, and a strong culture of teamwork, collaboration, and interdisciplinarity in the core department of the Center. The Center was credited with strengthening both. In addition, the University regarded the Center as a focal point for top-level research that involved teams of students, faculty, and industry, and saw it as a model to be emulated by other units and to be praised by the State Legislature.

NSF support for the CIE ended on September 30, 1999. By that time, a number of events had occurred that radically changed the Center's organization and structure. The key event was the establishment at the University of an NSF Materials Research Science and Engineering Center (MSREC) with two research foci (polymers and tissue engineering) that overlapped research thrusts in the CIE (polymer microstructures and bio-interfacial engineering). Organizationally and financially, establishment of the MSREC apparently outweighed any desire to keep CIE intact, so an agreement was reached that transferred the CIE polymer program to the MSREC, and terminated the bio-interfacial engineering thrust to avoid competition with the MSREC tissue engineering program for industrial support. Nonetheless, the University evidently wanted to sustain the highly successful level of overall interaction between industry and the University in the fields encompassed by CIE and the MSREC, to protect its investment in the Characterization Facility, to continue the CIE educational program, and obviously to build up the new MSREC; so it made alternative organizational arrangements to achieve these goals. The extent to which the culture of the new MSREC and related entities resemble an ERC is by no means clear. MSRECs have different objectives and criteria for evaluation than ERCs, so there is little reason to conclude that the ERC culture has simply been assumed in a new organization. On the other hand, the University clearly values most of the features that characterized the CIE and wished to retain them in some form, if not in a single organizational entity.

[17] *Center for Interfacial Engineering, Annual Report, Year Ten* (University of Minnesota, May 1, 1998): italics in original.

In summary, the CIE no longer exists as a separate organizational entity. Some programs have been terminated, some transferred to other units, and some (research) thrusts continued under the CIE name. But this does not mean that the Center disappeared without leaving a trace. At the time the CIE was initiated, the University's climate already was conducive to interdisciplinary research, but the highly successful CIE soon became a model for new centers that were created across campus. The CIE's activities in research, education, and industry collaboration were regularly touted to the state legislature, which evidently held this Center in high regard. Thus the CIE was initiated in an environment that already favored many Center-like features, and its success helped to foster similar activities during its tenure at the University. It served as a highly visible model for organizational arrangements and collaborations that the University valued.

PART III: FINDINGS AND CONCLUSIONS

Introduction

The 17 ERCs included in this study had many and diverse cultural impacts on the 16 university campuses in which the Centers were based (two of the Centers were at the same university). As is evident in the preceding accounts of individual Centers and individual campuses, these impacts were often subtle and difficult to disentangle from the impact of other influences upon engineering education and research – and even education and research more generally – in the nation's colleges and universities during the years after 1985, the date of the awards of the first cohort of ERCs. In this final section of this report, we provide a more cross-cutting look at the range of changes brought about by the earliest set of ERCs on the campuses at which they were located. As with the discussions of the individual ERCs, this section is organized around the following ERC Program objectives: a focus on next-generation engineered systems, strategic planning, interdisciplinarity, education, industry interaction, and overall impacts. The section concludes with an examination of the factors that help explain some of the differences in the degree to which individual ERCs contributed to change in the departments and other units most closely associated with them and within the colleges of engineering and the other colleges on the host university campuses more broadly. It also draws upon this examination to outline implications for NSF management of the ERC Program.

Engineered Systems

One goal of the ERC Program is to achieve major advances in next-generation engineered systems. Broadly, a system is a construct comprised of two or more elements that function in a coordinated fashion to yield some result. Engineered systems are designed and built by humans, are technical in nature, and produce a product or output that has economic and/or social value. The generic objective of achieving system-level goals was shared widely by ERC participants at every host institution, but the specific definition and operationalizing of the concept varied considerably both within and across host institutions. In site visit interviews, the terms "engineered systems" and "systems approach" seemed to mean all things to all people. As a consequence, each Center, and often individuals or groups within Centers, tended to define these concepts in their own way while trying to understand and meet NSF's requirement.

At several of the ERCs included in this study, the Center's engineered systems orientation was considered to be the core feature of the ERC that had led to broader impacts in a number of other areas. This was the case at the Carnegie Mellon Data Storage Systems Center, for example, where faculty desires to develop a systems-level approach to data storage were one of the chief motivating factors in the decision to apply for an ERC and was considered one of the primary influences on its educational activities and its industrial constituency. A similar sentiment was expressed by researchers at the Mississippi ERC, where the Center had invested heavily in a computational field simulation systems environment, which in turn was credited with much of the Center's success in technology transfer and industrial collaboration.

It was far more frequently the case, however, that Centers reported difficulty in arriving at agreement with NSF as to what constituted an appropriate engineered system. This was especially the case at those Centers that have a more conceptually based research agenda. At the University of Maryland, for example, despite the embodiment of this ERC Program goal in the name of the "Institute for Systems Research" and its predecessor "Systems Research Center," as well as the Center-initiated and -administered M.S. in systems engineering, Center participants reported recurring difficulties in convincing reviewers and NSF that it was in fact doing systems engineering research. In a number of other cases, faculty remained unclear as to just what the term meant, and some considered it little more than an NSF flag they had to salute.

Regardless of the extent to which the engineered systems approach was embraced by faculty and students directly involved in the Centers, the spill-over effects of this approach on other activities within the Colleges of Engineering or the on the campuses more broadly appear to have been negligible.

Strategic Planning

A key distinguishing feature of an ERC is strategic planning of the research, education, and technology development and commercialization activities of the Center. The strategic plan is for research intended to supply the framework on which the ERC's research project portfolio is organized and enable the ERC to communicate to each Center participant (faculty, students, industry personnel) about how his or her expertise fits into and enhances the entire Center's goals. According to the ERCs' *Best Practices Manual*, "The research strategy should identify what breakthroughs or developments in fundamental science and/or enabling technology are required initially, how they are interconnected, how further progress will build on these achievements and contribute to a convergence on the systems level, and which projects can and should proceed in parallel."[18]

The ERCs themselves are required to develop their initial strategic plans in the first 3 months and to submit annual updates of their strategic plans as part of their Annual Report to NSF. Strategic planning was therefore integral to the operations of each of the ERCs included in this study. In the vast majority of cases, the Centers had learned to value this planning process as a sufficiently important determinant of their future research direction that it remained a key management tool even when it was no longer required once the Center's ERC Program funding had come to a close.

The spillover effects of the Centers' strategic planning were difficult to discern – even in those departments most closely involved in the Centers' operations,. On some campuses, all departments and colleges, as well as the university's central administration, are required to develop strategic plans on a periodic basis. However, in no cases did we encounter an administrative unit other than the ERC itself in which the strategic planning activity that was taking place was even partially attributed to the influence of the Center. Nor did we encounter a single instance in which the specific type of strategic planning that is the hallmark of the ERC Program – identification of fundamental knowledge underpinning the enabling technology which comes together in the systems-level development – had spread beyond the ERC itself. This is not to say that the experiences of the ERCs with this type of planning process had no influence on the individuals who were involved in it which those individuals later applied in another, different setting in the university – only that none was specifically pointed to during the SRI

[18] *Engineering Best Practice Manual*, http://www.erc-assoc.org/chap3-2.htm.

interviews with ERC participants. Several of the universities, Carnegie Mellon in particular and North Carolina State to a somewhat lesser extent, had used a strategic planning process in an attempt – in both cases successful – to reposition the institution relative to perceived competitors. However, in most of the cases in which this type of concerted strategic planning at the upper administrative level of the university was apparent, it had predated the advent of the ERC.

"Strategic planning" writ large has become a generic descriptor – a "buzzword" – for the processes underlying institutional change or reorganization in many public and private sector organizations over the past decade or so. It is unlikely that this type of generalized organizational planning bears much resemblance to the ERC Program's strategic planning objective for a funded Center, which is much more specific and much more tailored to the related Program objective of the Center's specific engineered system focus driving the entire ERC's activities. The ERC Program goal that "An engineered systems focus and strategic planning drive an ERC's research" is directly applicable only in cross-disciplinary engineering center-type research operations similar to the ERCs themselves; so it is therefore not too surprising that few, if any, spillover effects of either of these ERC characteristics were found on the campuses examined in this study.

Interdisciplinarity

Engineering Research Centers contributed significantly to the development of interdisciplinary research and education at each of the 16 institutions hosting the Centers included in this study. The impacts were experienced primarily within Colleges of Engineering, and here, were most extensively evident in the departments most closely associated with the ERCs. However, impacts also extended in varying degrees to other colleges which participated in the ERCs, to strategies and priorities set by central administrations, and to university-wide policies related to promotion and tenure, allocation of indirect cost recovery funds, and management of specialized research facilities.

Increased acceptance and valuation of the formal structure required for interdisciplinary research centers and of the norms of collaborative, cross-disciplinary research were found alike on those campuses that historically had developed reputations for supporting cross-unit research centers and on those with little or no prior experience with interdisciplinary research centers. A cross-section of respondents, including university administrators, faculty, and ERC administrators involved in ERCs, as well as faculty and administrators not directly involved in ERCs, credited the university's ERC for many of the organizational, strategic, and cultural changes that had occurred on their campuses since the mid-1980s, although most respondents also noted that other convergent and reinforcing elements pointing to interdisciplinarity also contributed to these cultural and policy changes.

The common theme voiced by interviewees was that the ERCs served as an "existence theorem," – a proof of concept – demonstrating the feasibility of large-scale (relative to prior institutional experiences) collaborative, interdisciplinary research and interdisciplinary instructional programs producing significant contributions to fundamental engineering and scientific research and thus contributing to the development of new technologies, such as biofilm engineering. With one exception, most institutions credited the ERC with enhancing the professional reputation of the participating faculty, academic units, and the university as a whole. The one exception was the University of Colorado, where some respondents saw the ERC as leading to an undue emphasis on a marginal research field within the department's larger research agenda, and, in their view, leading to a diversion of departmental resources that in turn led to a reduced standing of the department in National Research Council rankings.

Most faculty who participated in ERCs commented positively on the contributions of an interdisciplinary orientation to their research. They also commented that they felt freer to participate in interdisciplinary projects because the general institutional environment, particularly at college and departmental levels, was more favorably inclined to accept interdisciplinary research. The approbation ranged from that of a Nobel Prize laureate at MIT, who commented that the linkage between the life sciences and engineering established by the ERC was indispensable to his institution's ability to remain a world-class research leader, to faculty at Montana State University, an EPSCoR institution, who commented on how the association formed by the ERC between departments of engineering and microbiology had led faculty to rethink fundamental research premises, and explore new laboratory and empirical techniques – at times thanks to the new, broader inclusion of students from collaborating departments in the laboratory.

In addition to contributions to the research performance of the university, the ERCs' emphasis on interdisciplinary research contributed to institutional goals of more relevant educational experiences and strengthened relationships with industry. On several campuses, ERCs became the exemplar underlying new institutional strategies to emphasize interdisciplinary research centers as part of a long-term strategy to promote institutional excellence in niche areas and to compete for federal and state government and industrial R&D funds.

The depth of the roots of interdisciplinary research on most ERC host campuses was seen as no longer dependent on the receptivity of the institutional environments. Rather, the extent to which faculty participate in interdisciplinary research was viewed primarily as a question of the availability of research funding. ERCs financed as well as advocated interdisciplinary research. There was a general attitude that the quantity of research performed on an interdisciplinary basis would decline without continued ERC Program core funding, not because of lack of interest on the part of the faculties involved but rather because they could not secure funds to continue as much research on that basis. Many faculty saw themselves as having to return to disciplinary-based funding sources, thereby requiring that they conduct their research on a narrower focus than permitted under the ERC model.

The thrust towards acceptance of the interdisciplinary mode of research and education promoted by the ERCs encountered several obstacles. The constraining force of these obstacles varied across institutions, ranging from a serious hindrance at one institution to development of collaborative relationships within a college of engineering and between the college and other colleges, to a need to constantly attend to apportionment of funds. Such conflicts were thought to arise because centers have the potential of creating an "us and them" mentality in the departments. The character and magnitude of these obstacles reflected a mix of institutional policies and personal interactions between and among ERC directors, college deans and department heads, and central administration officials. The institutional policies, as noted below, included indirect cost recovery, promotion and tenure, and space, and are readily described. Elements of interpersonal relationships related to perceptions of loyalty and control of faculty time, the characteristics of reporting relationships between the ERC director and other administrators and communication patterns also were noted by respondents as factors affecting the fit of the ERC with the larger institution, but no single pattern or guide to future behaviors is readily evident.

Indirect Cost Recovery

The most nettlesome issue to affect ERCs' relationships with other academic units across campuses was apportionment of indirect cost recovery funds attributed to the ERC's activities, including both its core NSF award and other research grants and contracts. Universities differ markedly in their policies towards distribution of these funds (Feller, 2000). Some treat all ICR funds as reimbursement for institutional expenses and direct these funds into the university's central budget, where they are allocated via the President and Provost's office to general university affairs, with little overt direct connection between the source of these funds (by research, academic unit, or research center) and their allocation from central administration to various units. Some institutions employ formulae to return a fixed percentage of funds to colleges or other established academic units based on their level of externally funded research, with subsequent distribution of these funds to sub-college units left to the discretion of deans, and, in turn, to department heads. Absent provisions to allow for both colleges/departments and centers to receive accounting credit for a research award, formula-based arrangements can create both the substance and appearance of zero-based games: a proposal that is submitted through an ERC or other interdisciplinary center may be perceived by the college(s) in which their faculty member(s) participate on the award as reducing the award base upon which their indirect cost recovery allocations are computed.

ICR funds are eagerly sought after by academic units. They constitute a core portion of unit revenues, needed annually to cover gaps between historic levels of operating expenses and university appropriations. ICR funds are used by academic units for cost-sharing for equipment, to provide in-kind and cash matches required or alluded to by external research sponsors, and as bridge funds between external research grants; they are also an important source of discretionary funds. The policies, formulae and administrator discretion associated with the distribution of indirect cost recovery is thus a latent source of friction on many campuses, whether or not they have ERCs.

Several features of the ERC Program, in particular, were the source of disagreements related to the distribution of indirect cost recovery funds. First, the size and national prestige associated with winning an ERC award in a national competition gave rise to new organizational and reporting relationships between central administrations and ERCs, at times giving the ERCs and their directors greater autonomy and control over budgets relative to deans and departments than had previously existed on several campuses. Second, to demonstrate institutional commitment in the competition for an ERC, some universities committed portions of the indirect cost funds provided for in the ERC budget back to the ERC, where they would be under the control of the ERC director; this tactic served both to commit and alter control of funds from deans and department heads to center directors. Third, the ERCs controlled sizeable amounts of money, both in terms of the NSF award itself and in terms of subsequent funding from industry and other sponsors of ERC research and educational activities. On several campuses, the ERC awards represented the largest single award ever received by the university; thus, the amount of indirect costs they generated were relatively large, as were the stakes over whether these funds would be allocated for use by the ERC or distributed to the college, where they were highly valued, both for their amount and because they represented discretionary funds.

Fourth, conceiving of and preparing a competitive ERC proposal is an entrepreneurial activity. Unlike departments and colleges, which are organizational fixtures, with roles and budgets that transcend the qualities of their administrative leaders, the establishment and viability of interdisciplinary research and education centers is more a matter of entrepreneurial initiative and leadership. In all but two of the early cohorts of ERCs included in this study, the initial push to establish an ERC represented the activities of a small number of senior faculty, often only one individual, who then became its director. Elements of conflict over control of resources and autonomy between ERC directors and deans and departments about resources are thus perhaps not surprising, albeit the magnitude of these conflicts and their toll on an ERC's influence upon the larger college and university environment appear to be more a matter of the individuals involved than of structural characteristics of the university. The exceptions are Brigham Young and Purdue University, where the Deans of Engineering were centrally involved in preparing the University's ERC proposal and shepherding it through its formative years. Colorado appears to have been one of the most contentious sites, with reports that a department head sequestered ("ripped off") what was to have been the ERC's indirect cost recovery share, although this situation was subsequently resolved.

Promotion and Tenure

The interdisciplinary and collaborative nature of ERC research and education runs counter to traditional notions of individual faculty research results published in a well-defined set of disciplinary-based journals. Hosting an ERC thus required a university to consider, and adjust as necessary, both its norms – i.e., values -- and policies for promotion and tenure. Awareness of the need to reconcile the nature of ERC faculty activities and output with pre-existing P&T practices was present on all but one of the campuses in this study. The exception was Carnegie Mellon, where interdisciplinary team based research was already well accepted or even embraced in P&T decisions.

The process of change and adjustment varied across campuses, ranging in most cases from subtle shifts in the criteria employed by P&T committees, to occasional formal institutional restatements of these criteria. More generally across campuses, in addition to generally stated formal institutional P&T criteria that faculty were expected to conduct and publish their research, the understood norm was that a faculty member was expected to have at least some portion of his research published on either a single-author, or more commonly, lead-author basis, with some number of publications appearing in journals closely aligned with departmental content, and that beyond this threshold level, collaborative articles, sometimes with industry co-authors, appearing in quality interdisciplinary journals would receive "credit" in the P&T process.

These adjustments in norms were not automatic. On many campuses, deans, department heads, and ERC directors spoke of having to "educate" departmental, college and university P&T committees about evolving modes of research collaboration and publications. On most campuses, the norms of single-authored, disciplinary research remained high. Still, most faculty in colleges of engineering spoke of national trends towards collaborative research publications in their fields. They noted that these trends were more likely to be recognized by deans and provosts and to a considerable degree by departmental committees, but not always by college-level committees, and even less so by university-level committees to describe emerging research and publication patterns in engineering. (This need extended to engineering research more generally, and was not confined to ERC activities alone). Given this larger trend, ERC collaboration in research and publications was seen more as a leading indicator of future trends in engineering scholarship and dissemination than as a unique or dissonant occurrence. In general, ERC directors and faculty spoke positively of the slow but steadily changing acceptance of collaborative, interdisciplinary research, again given a modicum of lead-author and disciplinary-based research output on the part of individual faculty members. Only a small number of cases were cited across the 16 campuses of junior faculty being discouraged from participating in an ERC from concern about how ERC-based research would be assessed by P&T committees. Only one campus showed evidence that institutional P&T policies or practices had led to several ERC faculty members being turned down for tenure because his/her research involved industry collaboration or sponsors and was published in collaborative and/or interdisciplinary journals. However, there were a number of campuses in which tenure battles surrounding ERC participants were occasionally described as "fierce", although in most cases the ERC Director was able to influence the final outcome.

Education

Education was the area in which the most widely spread impacts of ERCs were discernible on the 16 university campuses covered in this study. Although the effects of ERCs *per se* were often difficult to unravel from the many concurrent influences pressing for change in science and engineering education during the last decade, particularly at the undergraduate level, in every case but one at least some changes in the direction of increased interdisciplinary exposure, team-based research experience, industry interaction, and/or undergraduate involvement in research was at least in part attributed to the models set forth by the new curricula and courses, Research Experiences for Undergraduates (REU) programs, seminars and workshops, and other educational activities initiated by the ERCs. The changes attributable to the ERCs were most clearly evident in those departments with direct participation in the Centers, but were generally also apparent to at least some degree throughout the colleges of engineering. In some cases, the educational impacts of the ERCs were experienced as campus-wide phenomena, literally affecting practically all colleges and departments throughout the university.

Course and Curriculum Development

The impact of the ERCs on the courses and curricula offered by their host universities were substantial. Virtually all of the ERCs included in this study have created new courses and modified existing courses at both the undergraduate and graduate levels. Most of these courses were designed to reflect the interdisciplinary, systems-oriented research undertaken by the

Center. Enrollment in these courses by students not otherwise directly exposed to the ERC often served as a multiplier of the number of students the ERC was able to influence directly. Courses developed by the ERCs generally involved enrollment of students from multiple departments, thus providing faculty as well as students with an opportunity to interact with students outside their home departments. In a number of cases, company representatives were included in the Centers' design of these new courses or course modifications, thus bringing industry's thinking to bear on the content to which students would gain exposure. In some cases, industry representatives participate in Center-developed classes and symposia, either as lecturers or as students.

At a number of universities, the interdisciplinary courses developed by the ERCs were credited with leading to increased enrollment by students from one department in courses offered by another. At both MIT and Montana State, for example, engineering students, whether associated with the ERC or not, are increasingly enrolling in courses in biology. In 1993, MIT began requiring that undergraduate engineering students take at least some coursework in biology, which was attributed in part to the presence of the Bioprocessing ERC. At the University of Maryland, the new Project Gemstone, which reportedly stemmed largely from an attempt to emulate the observed educational accomplishments of the ERC, incoming students are placed in teams that cross all disciplines to work together throughout their college careers. The award-winning curricular changes introduced by the Carnegie Mellon Data Storage Systems Center in the electrical and computer engineering department were credited with leading to similar changes in the entire College of Engineering at CMU as well as in Engineering Colleges at other universities.

In addition to new or modified courses, many Centers have also developed or spurred the development of entire new degree programs. New degree programs are often cross-school, so courses are cross-listed, reflecting curricular changes broader than in engineering. The Maryland ERC, for example, developed a new M.S. in systems engineering, while the Purdue ERC has developed an M.S. option in manufacturing. As another example, the Mississippi State ERC developed a new M.S. and Ph.D. program in computational engineering, and was also considered instrumental in the initiation by the University of a new Ph.D. program in mathematics and an M.F.A in electronic visual imaging. At one institution, MIT, the Bioprocessing ERC was considered the catalyst for the creation by the University of a new multidisciplinary organizational structure within the College of Engineering to formalize the role of biology within the entire engineering curriculum. The new organizational unit will have the ability to hire and promote its own faculty, thus facilitating the hiring of truly interdisciplinary researchers and educators who might not be attracted or recruited by the more traditionally disciplinary bound departments.

One note of discord associated with new curricula or degree programs developed by ERCs was voiced on several campuses, especially some of the smaller institutions that have difficulty attracting high-quality engineering students at a time when engineering enrollments nationally are not growing. While the presence of the ERC *per se* was considered a major asset as a recruitment tool, the courses and degree programs offered by the ERC were seen as competing forces in enrolling those students, reducing the pool available for existing courses and degree programs. While the additional options provided by the ERC may well be in the students' best interests, faculty not associated with the ERC were often disgruntled by declines in enrollments in their own courses.

Undergraduate Involvement in Research

The active involvement of undergraduate students in Center research activities is a requirement of the ERC Program. Each of the ERCs therefore has at least one program through which undergraduates from their own university participate in Center research. Programs for students within their own institutions generally entail students working in research laboratories under the direction of ERC faculty and/or graduate student mentors. The undergraduates often receive either course credit or stipends for their work. They sometimes use the Center-based research experience for a senior honors thesis or design project. Their involvement with the ERC generally provides these students not only with exposure to research *per se*, but also to faculty and students from other departments within the university and to industry representatives who are visiting or working at the Center.

Many ERCs also have summer REU programs in which undergraduates from other universities join undergraduates from the center institutions and participate in the Center's research. Funds for REU students from non-ERC institutions can come from several sources. ERCs are allowed to compete for supplements to their base award to fund the involvement of undergraduates from these institutions who are women, underrepresented minorities, and persons with disabilities. REU support can also come in the form of separate awards made by the NSF REU Site Program. Finally, numerous ERCs use their own funds or obtain them from non-NSF sources to include additional undergraduates in REU activities.

The educational programs offered by the ERCs were generally considered a major attraction to industry. Students from these programs were not only viewed as better prepared for jobs in industry, but as having a better sense of what a career in industry was likely to be like. In many cases, the ERC was directly credited with a major change in the university culture surrounding involvement of undergraduate students in research. At Montana State, for example, the ERC was said to have been the first effort on campus to bring undergraduates into the laboratories. The Center developed a system in which graduate students mentor the undergraduates in much the same way that the faculty mentor the graduate students. It was a high profile part of the Center, and, in conjunction with other influences toward greater research experiences for undergraduates, has led to much more of this throughout the University. The University has now established a Coordinator of Undergraduate Research to facilitate undergraduate research experiences on the campus as a whole. At the Carnegie Mellon Data Storage Systems Center, relatively few undergraduates were involved as research assistants in the research activities of the Center's predecessor research operation; once ERC funding was received, however, undergraduates were drawn into the research effort, and frequently ended up publishing articles with their graduate student and faculty mentors. In other cases, the ERC's efforts at the undergraduate level were said to have come at a time where other forces on the campus were pushing in the direction of greater undergraduate research involvement, and to have reinforced or served as a model for programs or activities with related educational goals being established elsewhere in the university. In a few cases, however, the ERC itself was reportedly one of the few instances on the campus in which undergraduates had any real exposure to research and faculty in general remained resistant to the notion of involving undergraduates in their research in the belief that the degree of mentoring that would be required was more trouble than it was worth.

Graduate Programs

In most fields of science and engineering, graduate students receive a significant amount of support from faculty research funds and, as they progress through their department's degree program, they acquire increasing skills to become an important resource in the conduct of research. Typically, graduate research assistants work for individual researchers and move from relatively simple tasks, such as setting up apparatus or monitoring and collecting data from experiments, to taking on increasingly complex activities and responsibilities. Faculty mentorship usually takes place in the context of a departmental laboratory aimed at guiding the student toward a disciplinary degree. Student involvement in industrially sponsored research is often limited by the ability of projects to provide students with sufficiently complex problems to form the basis of a doctoral dissertation/thesis, and a graduate assistant's interaction with industry is often limited to the representative(s) of the sponsoring firm.

By contrast, graduate student involvement in an ERC is unique is several respects. First is the degree of cross-disciplinary interaction and exposure. While students typically work under the supervision of an individual ERC faculty member, individual faculty are part of ERC research teams that generally involve faculty and their students from multiple departments. ERC students are integral parts of these teams, exposing them to the thinking and problem solving skills and expertise brought from disciplines other than their own fields of concentration. Second, ERC students typically have considerably greater interaction with industry than is the norm. Industry personnel often work in the Center as fellows or adjunct faculty members, sometimes serving as mentors for students or members of their dissertation/thesis committees. Students themselves often do internships or other research at company locations. Poster sessions at which students present their research are often held in conjunction with ERC industrial meetings, affording industry representatives an opportunity to meet with students and learn about their work. ERCs frequently conduct their own seminar series at which students discuss their research with industry representatives as well as faculty and peers, or at which industry representatives present lectures.

The ERCs were often credited with serving as a major attraction in the recruitment of high quality graduate students, especially within those departments most directly involved. In a few cases, the presence of an ERC on the campus was credited with playing a role in an increase in the quality of students enrolling in the college of engineering more broadly. Graduate students generally reacted extremely favorably to the interdisciplinary course work as well as the research exposure they obtained through association with the ERC, and most were enthusiastic about careers in industry. Some, however, worried that the degree of interdisciplinary and problem-solving orientation of their ERC-associated educational experience might represent a disadvantage to their attempts to secure a position in academia, where the more traditional disciplinary orientation is far more common.

Impact Beyond ERC Host Institutions

Supplementary information on the impacts of ERCs is provided by the findings from a somewhat related SRI study that in part addressed educational reforms at the undergraduate level being introduced in colleges of engineering in U.S. universities. As part of that study, a survey was conducted in 1999 of Engineering Deans of 231 colleges and universities that have undergraduate engineering programs. Of the 231 Deans to whom questionnaires were distributed by a combination of e-mail and web-based administration, 185 valid responses were received, for a response rate of 80%. Universities at which ERCs were formerly or at that time based (including both host and partner institutions) represented 35 of the 231 colleges and universities surveyed. Of the 35 ERC institutions, responses to the questionnaire were received from 30, or 86% of the total.

Questionnaires were addressed by name to the Deans of the schools/colleges of engineering, with a cover letter noting that the Dean might wish to have the questionnaire completed by another individual in the university administration with special knowledge of engineering curriculum issues, for example, and Academic Affairs Officer or the chair of the engineering curriculum committee. More than two-thirds of the responses (70%) were completed by the Deans of engineering *per se*, and another fifth (20%) were completed by the associate/assistant Deans for academic affairs (see Table 30). The remaining ten percent were completed by vice presidents/vice provosts for academic affairs, associate/assistant Deans for engineering, Deans of the undergraduate college or academic programs, and in one case by the provost. None of the questionnaires had apparently been referred to a curriculum committee chair for completion.

When institutions in which ERCs were based as of 1999 are separated from other colleges and universities included in that survey, some interesting findings about cultural changes in institutions associated with ERCs emerge. As with the findings from in-person interviews or a review of ERC annual reports, survey results can be attributed to the presence or absence of an ERC on campus only tenuously at best. However, they do have some bearing on the overall findings of this study, and are presented here for that reason.

Table 3 shows the types of undergraduate education reforms initiated at U.S. colleges of engineering during the five years preceding the survey. Compared with other institutions, engineering colleges associated with ERCs consistently reported a greater tendency to have initiated reforms of all types with the exception of changes in the freshman core sequence, and a significantly greater tendency to have increased the emphasis on recruitment and retention of underrepresented groups. In addition to recruitment and retention reforms, more than three-fourths of ERC institutions reported having instituted reforms of the following sort: course design, development, or revision; use of computer-based instruction; use of new instructional techniques; team teaching of courses or labs; increased involvement of undergraduate students in research; changes in freshman core sequence; and use of video (TV, tapes, direct feed). The involvement of undergraduate students in research, which 80% of ERC institutions reported having initiated during the preceding five years, is one of the core objectives of the ERC Program. Interestingly, and consistent with the above noted lack of agreement about the operational meaning of the term, less than a fourth of ERC institutions reported having adopted an engineered systems approach to undergraduate education, only a fraction above the number of non-ERC institutions that reported having done so.

Table 4 shows the primary factors that engineering deans considered as having motivated the reforms taking place in their institutions over the preceding five years. The top five motivating factors reported by ERC institutions, reported by three-fourths or more of respondents, included faculty interest, administration interest, industrial advisory board interest, student interest, and ABET 2000. One statistically significant difference between ERC institutions and non-ERC institutions is that ABET 2000 was reported as a factor motivating reform at 92% of non-ERC institutions, compared to 77% at ERC institutions. This may relate to the fact that internal interest in reform on the part of administrators, faculty and students was considerably higher in ERC institutions than non-ERC institutions, where external pressures may therefore have had a greater influence. Just over half of the ERC institutions reported that the presence of an ERC at that institution had been a factor motivating reform in the college of engineering.[19]

Table 3
Undergraduate Education Reforms Initiated During the Past Five Years
(Percent of Respondents)

	All Institutions N=185	ERC Institutions N=30		Non-ERC Institutions N=155
Course design, development, or revision	97.8%	100.0%		97.4%
Use of computer-based instruction	89.2%	93.3%		88.4%
Use of other new instructional techniques	75.7%	86.7%		73.5%
More emphasis on recruitment and retention of underrepresented groups	76.2%	93.3%	*	72.9%
Team teaching of courses of labs	73.5%	86.7%		71.0%
Changes in freshman core sequence	76.8%	76.7%		76.8%
Increased involvement of undergraduate students in research	72.4%	80.0%		71.0%
Use of video (TV tapes, direct feed)	63.8%	76.7%		61.3%
Changes in methods of assessing students	62.7%	70.0%		61.3%
Increased involvement of faculty in undergraduate teaching	48.1%	60.0%		45.8%
Development and management of large scale curriculum changes	36.8%	46.7%		34.8%
Adoption of an engineered systems approach	22.2%	23.3%		21.9%
Other	13.5%	20.0%		12.3%
None of the above	0.5%	0.0%		0.6%

Source: SRI International, Survey of Deans of Schools of Engineering, 1999.
***Statistically significant difference between ERC and Non-ERC Institutions at p<.01 level.*
**Statistically significant difference between ERC and Non-ERC Institutions at p<.05 level.*

Table 5 shows the proportion of faculty in colleges of engineering who reportedly engage significantly in interactions outside their departments. With the exception of interaction with K-12/14 students, ERC institutions consistently reported a greater percentage of faculty interacting with other departments, other colleges within the university, and with industry. Only in the case of interaction with industry, however, were the differences statistically significant. Roughly 60% of ERC institutions reported that more than 50% of their faculty engage in significant interactions with industry, compared with 32% of non-ERC institutions that reported that degree of industry interaction.

[19] The 5% of non-ERC institutions that reported the presence of an ERC as a factor motivating reform are not involved with an ERC, even as a secondary collaborating institution. We can only surmise that these institutions have some sort of entity on their campuses that they think of as an engineering research center, although not necessarily in the sense of what is meant by an NSF ERC.

Table 4
Factors Motivating Reforms in Schools/Colleges of Engineering
(Percent of Respondents)

	All Institutions N=185	ERC Institutions N=30		Non-ERC Institutions N=155
ABET 2000	89.7%	76.7%	*	92.3%
State and/or system-wide mandate	30.3%	33.3%		29.7%
To achieve a better fit with preparation of incoming students	43.8%	50.0%		42.6%
Student interest	53.5%	76.7%	**	49.0%
Faculty interest	78.4%	90.0%		76.1%
Administration interest	61.6%	80.0%	*	58.1%
Industrial advisory board interest	66.5%	80.0%		63.9%
Industrial employer interest	63.8%	70.0%		62.6%
Interest of other outside sources (e.g., funding agencies, foundations or donors)	30.8%	33.3%		30.3%
Engineering Research Center at the institution	13.0%	53.3%	**	5.2%
NSF's Engineering Education Coalitions Program	27.0%	46.7%	**	23.2%
Other	7.6%	6.7%		7.7%
None of the above	0.5%	0.0%		0.6%

Source: SRI International, Survey of Deans of Schools of Engineering, 1999.
***Statistically significant difference between ERC and Non-ERC Institutions at p<.01 level.*
**Statistically significant difference between ERC and Non-ERC Institutions at p<.05 level.*

Table 5
Proportion of Faculty in Schools/Colleges of Engineering
who Engage Significantly in Interactions Outside their Departments
(Percent of Respondents)

	All Institutions N=185	ERC Institutions N=30	Non-ERC Institutions N=155
Interaction with other departments			
Less than 10%	10.3%	3.3%	11.6%
About one-third	56.2%	60.0%	55.5%
More than 50%	33.0%	36.7%	32.3%
Don't know	0.5%	0.0%	0.6%
Interaction with other colleges			
Less than 10%	47.0%	36.7%	49.0%
About one-third	43.8%	53.3%	41.9%
More than 50%	7.0%	10.0%	6.5%
Don't know	2.2%	0.0%	2.6%
Interaction with industry**			
Less than 10%	10.8%	0.0%	12.9%
About one-third	51.9%	40.0%	54.2%
More than 50%	36.2%	60.0%	31.6%
Don't know	1.1%	0.0%	1.3%
Interaction with K-12/14 students			
Less than 10%	75.1%	83.3%	73.5%
About one-third	20.0%	16.7%	20.6%
More than 50%	2.7%	0.0%	3.2%
Don't know	2.2%	0.0%	2.6%

Source: SRI International, Survey of Deans of Schools of Engineering, 1999.
***Statistically significant difference between ERC and Non-ERC Institutions at p<.01 level.*

Table 6
Weighting of Undergraduate Education Reform Activities in Promotion and Tenure Decisions Relative to 5 Years Ago (Percent of Respondents)

	All Institutions N=185	ERC Institutions N=30	Non-ERC Institutions N=155
In Promotion Decisions			
Innovative teaching is currently valued:			
More than 5 years ago	44.9%	53.3%	43.2%
About the same	52.4%	43.3%	54.2%
Less than 5 years ago	0.5%	0.0%	0.6%
Don't know	2.2%	3.3%	1.9%
Curricular reform activities/efforts are currently valued:			*
More than 5 years ago	37.3%	56.7%	33.5%
About the same	58.4%	40.0%	61.9%
Less than 5 years ago	2.2%	0.0%	2.6%
Don't know	2.2%	3.3%	1.9%
In Tenure Decisions			
Innovative teaching is currently valued:			
More than 5 years ago	43.8%	53.3%	41.9%
About the same	50.8%	43.3%	52.3%
Less than 5 years ago	1.1%	0.0%	1.3%
Don't know	4.3%	3.3%	4.5%
Curricular reform activities/efforts are currently valued:			
More than 5 years ago	33.0%	50.0%	29.7%
About the same	60.0%	46.7%	62.6%
Less than 5 years ago	2.2%	0.0%	2.6%
Don't know	4.9%	3.3%	5.2%

Source: SRI International, Survey of Deans of Schools of Engineering, 1999.

**Statistically significant difference between ERC and Non-ERC Institutions at p<.05 level.*

Industry Interaction

The Engineering Research Centers Program was established in the initial phase of expanded federal and state government endeavors in the 1980s to foster long-term relationships between U.S. universities and industry, with the view towards stimulating national and state economic competitiveness. The long-term relationships were to encompass research, education, and technology transfer.

The ERC Program also began soon after legislative enactment of the Bayh-Doyle Act (1980), which among its provisions permitted universities to file for patents on findings flowing from (U.S.) government-sponsored research. Bayh-Doyle spurred major rethinking on the part of universities regarding their policies and practices towards patents, and led many research institutions to revise (or establish) intellectual property rights policies, expand their IP offices, and approach research findings from a new, more proprietary perspective. In addition, technology transfer policies were evolving continuously (normally shifting in emphasis from license review to looking for licensees, establishing equity holdings, and spinning off firms) during the years in which the institutions included in this study hosted an ERC, thus making it even more difficult to attribute specific policy changes to the presence of an ERC. Only at MIT, where the University's IPR policies had been put in place during the 1930s, were there said to have been relatively few changes in these policies in the years since the ERC was established.

Long-term University-Industry Partnerships

The ERC Program had major, discernible impacts on how universities perceived, valued, and organized their interactions with industry. The impacts on research and education were widely regarded as positive. These impacts built upon and at times helped shape the trend towards increased and closer collaboration between universities and firms throughout the 1980s, as reflected in the increased percentage of academic R&D funds supplied by industry and the spread of university-industry-government cooperative R&D centers across much of American research university systems (Cohen, Florida, and Goe, 1994). Positive impacts associated with the presence of an ERC are reported on every campus included in this study, although on some (e.g., Mississippi State) the degree to which the level of interaction with industry of those faculty who participated in the ERC differed from that of non-ERC faculty was questioned by some interviewees.

For institutions with a long history of involvement with industry, such as MIT, Purdue, and Carnegie-Mellon, ERCs brought a larger, more sustained level of interaction. For other institutions, such as Montana State University and Brigham Young University, the ERC created a scale of interactions that the university had not previously experienced, yielding new appreciation of the opportunities available to firms that, with proper safeguards, would permit the institution to expand its research program without detracting from other university objectives or norms.

Faculty and administrators at several universities noted that they recognized that industrial funding was necessary to maintain a stable research program, given the economic and political vicissitudes surrounding federal government funding of academic research. Faculty at public universities also commented on the growing pressures for the university to become a more active contributor to the state's economic well-being. Thus they perceived a push coming down through the institution for increased involvement with industry, with recruitment emphasis on working with in-state firms, especially small firms. (Faculty also noted that these pressures bore limited relationship to their sources of industrial funding, which at most ERCs predominantly came from large, often multinational firms).

Dealings with industry also often required new understandings and negotiation skills on the part of the university's office of sponsored research projects. In their new dealings with industry, faculty at times complained that sponsored research administrators were unfamiliar with industry practices, such as fixed-price contracts and invention disclosures. Here again, faculty in ERCs were among the early researchers on several campuses to encounter what they perceived to be slow or low-quality services provided by the university's research support infrastructure and often ended up themselves serving as instruments of change.

Intellectual Property Rights

The ERCs had modest impacts on the formulation of university intellectual property rights policies across the host campuses, primarily because the Bayh-Doyle Act had already set in motion a widespread, often fundamental rethinking and restructuring of the university's patent and licensing policies on most of them. Controversies and disagreements surrounding intellectual property rights policies – e.g., mandatory assignment of rights to the university and apportionment of royalty and license income – were reported on several campuses, but few of those differences were associated with the ERC.

ERCs were important in two somewhat contradictory ways across the institutions. First, on some campuses, the more frequent and intensive interactions of the ERC with firms created the first or early "cases" that either directed the shape of a university's new policies or were the specific settings about which general policies become converted into case practice. Second, in a quite opposing way, the ERC's previous or proposed IPR agreements with its subscribing firms sometimes ran counter to existing university policies. In some cases, ERCs sought waivers or exceptions from university policies, grounding these requests on the arguments that ERCs were "unique," that they offered special visibility and prestige to a university, and that potential revenues to be gained by a strict adherence to institutional policy was less than the revenues – federal, state, and industrial – garnered from operating differently as an ERC.

The University of Maryland, for example, witnessed major changes in its IP and technology transfer policies beginning in the mid-1980s, but these changes were seen as derived from national trends towards increased University involvement in "active" technology transfer, as well as additional pressures placed on public universities by state governments for these institutions to become engines of regional economic growth – not to any specific events associated with the Institute for Systems Research. Similarly, University policies were liberalized in the early 1990s to permit increased faculty involvement in spin-off firms related to their research, but this change appears to have been shaped by new opportunities for faculty researchers in biotechnology and information technology to launch firms, not by commercialization of ISR-based research.

The site visits indicate several specific examples of how ERC operations highlighted the need for a university to reconsider its intellectual property rights policies, as well as some cases of divergences between general university patent and licensing policies, old or new, and arrangements entered into by a ERC and its contributing firms. In general, however, ERCs were not the major causes of changes in institutional patent and licensing policies or strategies; rather, these changes emerged from the confluence of several factors, including court decisions (e.g. Diamond vs. Chakrabarty), federal legislation (e.g, Bayh-Dole), academic leadership in scientific advances of high commercial potential (e.g. microbiology), a search for increased discretionary revenues by both public and private universities, and, as noted, the desire by universities to demonstrate their contributions to national and state economic growth.

These events have produced substantial increases in the absolute number and relative importance of academic patents to total U.S. patents, an increase in the number of universities filing for and receiving patents, increases in the number of universities with internal technology licensing offices, as well as increased revenues from intellectual property and participation in spin-off firms. The result of these changes over time, however, is to bring the mainstream of intellectual property rights policies and practices closer to the ERC core objectives of fostering technological innovation and the transfer of academic research. Differences among universities that host ERCs are today more likely to reflect specific institutional settings (e.g., differences among universities in preferences for equity holdings relative to royalty income or in conflict-of-interest policies) than in core philosophies or policies.

Overall Impacts

To a considerable degree, the objectives set forth in the initial formulation and establishment of the ERC Program have entered the mainstream of discourse about the desired ends, structure, and activities of America's research universities. This trend complicates disentangling the impacts of ERCs from other convergent influences. Many of the cultural-change objectives, such as the emphasis on interdisciplinarity or increased industry interaction sought by the ERCs, accord with broader calls for reforms in the characteristics of knowledge generation and dissemination in America's research universities (Boyer, 1990). Gibbons et al. (1994), for example, have trumpeted what they term the coming ascendancy of Mode 2 over Mode 1 forms of knowledge. In their framework, Mode 1 corresponds to academic-, discipline-, and department-based knowledge, and carries (invidious) distinctions between basic and applied research. Mode 2, by contrast, is transdisciplinary, emphasizing the constant interplay between basic and applied research.[20]

In a related manner, the ERC Program objective to foster long-term university-industry interaction about industrially relevant, problem-focused research, with its attendant implications for team-based, cross-disciplinary research and greater exposure of undergraduate and graduate students to industrial problems and work environments, anticipated subsequent calls for reform in education in science and engineering. For example, as noted in the 1995 NAS (Griffith) report, *Reshaping the Graduate Education of Scientists and Engineers*, since the early 1970s the trend has increasingly been toward employment of recent science and engineering Ph.D.s in more applied research and development and more diversified, even nonresearch employment, and away from positions in education and basic research. The report further notes that industrial firms favor potential employees who: "Can collaborate across disciplines, in various settings, and learn in fields beyond their specialty; Can adapt quickly under changing conditions; Work well in teams and demonstrate leadership ability; and Can work with people whose languages and cultures are different from their own" (p. 2-25).

These calls likewise echo themes in the ERCs' educational objectives towards having graduate and undergraduate students actively participate in problem-focused, interdisciplinary research projects that involve the integration of theory and practice and that also involve the participation of both faculty and industrial researchers.[21] Studies by SRI (Ailes, Roessner, and Feller, op. cit.) and Abt (1996) report that participating firms perceive that new employees who were involved as students in ERCs outperform comparable groups of new employees who did not have that experience. According to the Abt study, "Graduates perceived ERC-linked experiences as having a somewhat more positive impact than general experiences on performance in areas such as technology transfer, understanding relationships between work and clients, networking within the organization or field, and ability to work in interdisciplinary teams; these are areas which have been special targets for ERC efforts" (Abt, *op. cit*., p. iv).

Frequency of calls for reform is not, however, synonymous with actual change. ERCs represent one of a series of efforts to alter if not the missions of research universities, then at least their functioning and outputs, both research and educational, better to meet the needs of a number of their existing constituencies – especially students – as well as those of new, or relatively more important, constituencies. In all of this, there is both a challenge and a criticism, variously explicit or implicit, about the performance of universities based on the generation of specialized knowledge organized into disciplines and departments. As described by Gumport, the evolution of the American research university was based on the integration of research and graduate degree programs with longer-standing undergraduate degree programs within the same institution, involving the same faculty organized about departmental structures: "This organizational arrangement permitted control of undergraduate and graduate programs to reside within the same faculty. Coursework as well as research training could be designed appropriate to each discipline and coordinated by each department's faculty. One functional by-product of this arrangement was that graduate programs maintained both faculty and institutional continuity: they allowed faculty to reproduce themselves by training their professional successors; and they promoted cohesion of the university, since the responsibility for graduate students kept faculty attentive to their departments (Gumport, 1991, p. 105; also Geiger, 1986).

With all these positive indicators, however, it would be incorrect to speak of wholesale change in the structures, activities, or norms of academic research, education, and technology transfer, whether on the part of the university or of colleges of engineering which are the immediate organizational homes of ERCs. Thus, to cite technology transfer as an example, despite general findings of changes in faculty attitudes supportive of increased university involvement in technology transfer (Peters and Etzkowitz, 1990; Lee, 1995), Tornatzky and Bauman pointed to the "outlaw" character of faculty involvement in technology transfer: "And make no mistake that in all too many universities, those faculty who do become involved in cooperative research relationships with industry, or technology patenting and licensing, or commercialization of inventions, will not be treated well at the hands of peers and administrators . . . When it comes time for evaluation, these . . . faculty come to understand that refereed journal articles in one's discipline account for much, and patents and interdisciplinary articles count for much less" (1997; pp. 2-3).

Similarly, calls for greater interdisciplinary/cross-disciplinary research in academic and instructional areas appear with cyclical regularity (Friedman and Friedman, 1985). These calls

[21] Assessment of the educational impacts of the ERC indicate that these objectives are being attained.

represent recurrent views that the configuration of knowledge resident within specific academic disciplines and departments, and the constraints placed by this "traditional" organizational design on the selection and conduct of research projects, causes academic research to lag behind the real-world context in which interesting and important problems exist.

The difficulties encountered in establishing viable interdisciplinary programs on American campuses and the special problems associated with creating (and protecting) a niche for interdisciplinary, industrially relevant research centers and institutes on America's campuses are well recognized (Mar, Newell, and Saxberg, 1985, pp. 193-200; Stahler and Tash, 1994; Friedman and Friedman, 1985). These difficulties derive from the propositions that disciplines, because they are based on the concept of specialization, "are efficient and productive ways of organizing research (Stigler, 1963); and that scientists are unlikely to concentrate on specialized work unless they can achieve recognition from fellow experts of their discoveries…[and that] the institutionalization of a specialty has a decisive impact on the quality of accomplishment, for professionalization . . . requires that formal positions in institutions provide opportunities for performing the specialized tasks as part of occupational careers" (Blau, 1973, pp. 196-197). Indeed, the parlous state of interdisciplinary programs in America's research universities was singled out for attention in a Government–University–Industry Research Roundtable (GUIRR) report: "Despite consensus that much exciting and important research is done at the interface of traditional disciplines, there are many barriers to effective multidisciplinary research and teaching in all components of the system—both within federal agencies, as they offer research support, and within universities, whose structures and rewards systems fail to facilitate this type of collaboration" (1994, p. 7). The GUIRR report goes on to note that the barriers to collaboration relate to "personal careers and academic culture, and those that are administrative in nature. Within academic institutions . . . the nature of tenure and promotion discourages multidisciplinary work, reinforcing instead single-authored research and publications conducted within traditional disciplinary boundaries" (p. 7).

While institutional advances towards increased interdisciplinarity were observed at ERC institutions, especially in selected engineering, science and a few social science/humanities fields, systematic advances towards interdisciplinary approaches to education and research still remains an upward struggle at many research-intensive universities, again allowing for variations among fields and universities. As noted by Rodney Erickson, Provost of Pennsylvania State University, for example, in a 1999 conference on interdisciplinarity: "To encourage interdisciplinary activity, we need to take a hard look at what the barriers are and then devise ways to minimize the barriers. For example, some departments lay out journal lists – "A" journals, and so forth. I believe in the highest standards of academic excellence, but I find this approach incredibly stifling, and counterproductive in broadening the scope of influence of departments and disciplines" (p. 171-173).

Implications for NSF

SRI examined a number of variables that might help explain differences observed in the degree to which ERCs had impacted their host universities along various dimensions. The first set of variables had to do with characteristics of the host institution itself. These included the following:

- Public or private;
- Carnegie classification;
- Size of enrollment;
- Percentage of graduate degrees awarded in engineering;
- Rank among U.S. colleges and universities in terms of R&D funding;
- Percentage of R&D funding derived from industry;
- National Research Council departmental effectiveness rankings; and
- *U.S. News and World Report* ranking of graduate engineering program in general.

We also examined a set of variables that related more specifically to characteristics of the ERC itself. These included the following:

- Number of departments involved;
- Degree of participation from outside the College of Engineering;
- Degree of systems orientation;
- Degree of industry involvement;
- Degree of student/industry interaction;
- Prominence of the Center's educational programs with the College of Engineering or the university more broadly;
- Degree of undergraduate student involvement;
- Primary campus location (central or more remote); and
- Degree of university administration's interest in and interaction with the Center.

Our analysis also took into account the extent to which ERC-like characteristics (center-based research, strategic planning, engineered systems approach, interdisciplinary research and education, undergraduate involvement in research, industry involvement) were common or unusual in the broader institutional environment prior to the establishment of the ERC, and the degree of change that appeared to have occurred since the Center's inception. Additionally, we were interested not only in the perceived degree of change at the broader institutional level, but the extent to which such change might reasonably be attributed to the presence of the Center in that environment.

The resulting analysis of ERC impacts on the culture of the institutions in which they are based showed that there are few, if any, structural characteristics at the institutional level itself that account for high or low impacts of the Center on the institution more broadly. Results were widely dispersed among public and private institutions, relatively small and large and extremely large universities, those with extensive and those with modest R&D funding overall as well as percentage funded by industry, and those institutions with extremely high and relatively low rankings of quality of their engineering programs. The pattern was also for the most part fairly dispersed in terms of variables associated with the ERCs themselves, but a few characteristics in this case seemed to be at least somewhat correlated with the degree of positive impacts. These included high prominence of the Centers' educational programs, a high degree of undergraduate involvement, a central campus location, and a high degree of administration interest in and interaction with the Center.[22] Given the obviously small number of observations we have, the striking finding still remains the dispersed pattern that exists for almost all variables.

One hypothesis that was explored and discarded was the notion that ERCs based in smaller institutions might be likely to have greater institutional impacts than those based in large ones, simply because the sheer size of the activity would make it that much more prominent. On the contrary, ERCs with high institutional impact were located at large as well as relatively small institutions. Another was that ERCs based in institutions that already embody many of the characteristics ERCs are designed to promote would allow little leeway for the ERCs to further the manifestation of such characteristics. Among the ERCs that appeared to have had the greatest impact on change within their host institutions was a Center based in one of the institutions most highly hospitable to ERC-like characteristics at the time the Center was established, as well as one among the least (the degree of change in each institution was similar, although, of course, the latter did not rise to the level of hospitableness to ERC-like characteristics that the former had even prior to the ERC).

Finally, although two of the Centers that were among the highest in terms on institutional impact involved extensive involvement by the College of Science as well as Engineering, in a third Center that also had a great deal of impact this was not the case. However, that third Center did become the locus for cross-institution interdisciplinary educational initiatives that were equally significant in broadening the exposure to the ERC-like culture within the institution as a whole. This suggests that the more closely intellectually and/or structurally bounded the ERC is, the less likely it is to play a leadership role in change at the broader university level.

This study, as the previous SRI study that examined the transitions to self-sufficiency of mature ERCs, also points to the considerable importance of strong support and interest on the part of the higher administration in the degree of success a Center is likely to have in meeting the broader goals of NSF's ERC Program. While it may be difficult for NSF reviewers to assess the presence of this factor at the initial proposal stage, it should certainly be made clear to awardees that it will be an important criteria in subsequent intermediate and renewal reviews.

[22] Write footnote noting that most of these also correlated with success at transition to self-sufficiency.

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APPENDIX A:
INTERVIEW GUIDE

ERC INSTITUTIONAL IMPACTS
INTERVIEW GUIDE

INTRODUCTION

SRI International, under a Task Order from the National Science Foundation, is conducting a study of institutional changes associated with the Engineering Research Centers (ERCs) program. We are specifically interested in interactions between the ERC program and the following changes in research and education activities that may have occurred at the university in which the ERC is based:

*engineering systems (integrative) approach to research and education;
*team-based approaches to research and education;
*interdisciplinary research and education;
*shared use of equipment among faculty and academic units;
*involvement of graduate and undergraduate students in research;
*interaction with industry and technology transfer;
*strategically oriented research management.

Our interest is in initial settings prior to the creation of the ERC, changes induced by the ERC, and the projected continuation of these changes.

(NB: These questions are intended to guide the interview. Phrases in parentheses are probes to pursue questions in greater detail.)

A. ADMINISTRATORS (CENTRAL ADMINISTRATION, DEANS, AND DEPARTMENT CHAIRS)

In terms of the above institutional characteristics:

A1. Describe what you perceive to be prevailing policies, practices, and culture prior to the establishment of the ERC.

A2. Describe the major impacts of the ERCs on the culture of engineering research and education within your college and university (Probe for "early years" and "current" impacts).

A3. Which attributes of the ERC (e.g., equipment, facilities, organizational structure) have contributed most to these impacts?

A4. What other impacts, if any, has the ERC had on the research and educational culture of your unit (university)?

A5. Describe any extension of the ERC's ways of conducting research and educational activities to other departments or colleges in the institution.

A6. In what way(s), if any, has the ERC's impact different from that of other interdisciplinary research units in your institutions (e.g., Materials Research Laboratories)?

A7. Have these other changes occurred as a result of formal planning or informal imitation?

A8. What, if any barriers were encountered (or are expecting) in adopting the ERC's modes of operation to other units?

A9. To what extent are the cultural influences or institutional impacts of the ERC highlighted in the university's (college's/department/s) strategic plans, organizational relationships or budget priorities?

A10. (For those universities in which an ERC is nearing its maximum years of NSF support) Describe any planned policies or initiatives designed to institutionalize the cultural changes attributed to the ERC.

A11. Identify any ERC directors or other university administrators who were centrally involved in the ERCs early history who are no longer at the university.

B. ERC DIRECTOR/FACULTY PARTICIPANTS

B1. Describe the characteristics of research projects or activities of ERC research groups emerging from the ERC in terms of:

a) engineering-systems approach;
b) shared use of equipment;
c) team-based research;
d) interdisciplinarity;
e) involvement of graduate and undergraduate students;
f) involvement of industry.

B2. How does ERC research differ from what ERC faculty did before the ERC?

B3. Provide documentation (or review documentation from ERC annual reports) on the following:

a) Number of faculty engaged in projects with the above characteristics;
b) Number of articles with joint authors from more than 1 department (within Engineering, and between Engineering and other colleges, especially Science);
c) Number of professional presentations with authors from more than 1 department (college);
d) Number of research proposals (other than that involving ERC funding) with investigators from more than 1 department (college);
e) Number of patents with faculty from more than 1 department.

B4. Describe how participation in ERC activities has affected:

a) Choice of research topics;
b) Choice of methodology;
c) Choice of collaborators;
d) Mode of collaboration;
e) Involvement of graduate and undergraduate students in research;
f) Composition of dissertation committees;
g) Source(s) of external funding;
h) Planning at research group and center level;
i) Type/range of work done within the ERC (e.g., development; prototyping; use of testbed facilities).

B5. What difference, in any, exists in the selection of the journals in which faculty in the ERC seek to publish research findings?

B6. Are there appropriate cross-disciplinary journals in which ERC faculty can publish their collaborative research? Have ERC faculty had to break up their results to publish in disciplinary journals?

B7. Describe any institutional changes in culture, policies, or programs at the department, college, or university level that you attribute to the ERC model.

B8.Have these other changes occurred as a result of formal planning or informal imitation?

B9. What, if any barriers were encountered (or are expecting) in adopting the ERC's modes of operation to other units?

B10. Which, if any, of these changes would you expect to be maintained by your department/college/university independent of the ERC, once "graduation" has occurred?

B11. In what way, if any, have these changes affected your personal or unit's interaction with federal or industry sponsors of research beyond NSF's ERC program (e.g., research grants and contracts).

B12. What weight is accorded by department heads and department faculty to publications (and related professional activities) based on team-based projects, interdisciplinary projects, or projects that employ an integrative approach to engineering research (relative to similar activities that appear in disciplinary-based journals and forums)?

B13. What weight is accorded by department heads and department faculty to working with industry, receiving industrial support, receipt of a patent, and spinning off firms?

C. ERC STUDENTS (GRADUATE AND UNDERGRADUATE) (NB: Sort responses by level of degree: Ph.D., MS, undergraduate)

C1. Describe your activities in the ERC.

C2. With how many faculty outside your department have you interacted as a result of participating in ERC activities?

C3. How has participation in the ERC affected your choices with respect to:

a) Major field of study;
b) Research interests;
c) Methodological approaches to research;
d) Course selection;
e) Career plans;
f) Graduate school plans;
g) Dissertation (Honors thesis) topic.

C4. To what extent do you perceive these choices to be different from those students who have been research assistants on project-based grants and contracts?

C5. What problems, if any, did you encounter in working with faculty in other disciplines?

C6. What educational or research benefits, if any, did you derived from participating in an ERC (relative to working on a single PI-type project)?

C7. In what ways, if any, do you perceive your education to have been different from those of your classmates (who did not participate in ERC research or other ERC activities)?

(NB: Probe whether friends have been involved in team-based research or interdisciplinary projects or courses, or interacted with industrial representatives).

C8, To what extent, if any, are a student's relationships with faculty members in ERCs different from those with non-ERC faculty?

D. NON-ERC STUDENTS

D1. In what ways, if any, have you worked on research projects with

a) students from other departments;
b) faculty from other departments;
c) industry researchers.
(For Ph.D. students)
a) Describe the composition of your dissertation committee.

D2. In what ways, if any, has your education differed from your classmates who have participated in ERCs (NB: Probe whether friends have been involved in team-based research or interdisciplinary projects or courses, or interacted with industrial representatives).

D3. Did you have an opportunity to participate in the ERC?

D4. If yes, why did you choose not to participate?

D5. What, if any, alternatives to the ERC exist in your field to provide experiences such as team-based research, engineering-systems approach to research and education, interaction with industry, etc?

D6. Assuming equal levels of financial support, assess the benefits and costs of working as a graduate assistant for a single faculty member relative to those of working for a faculty member who participates in an ERC.

E. FACULTY REPRESENTATIVES

E1. Assess the importance of each of the following in your university's practices and strategic plans:

a) team-based research and education;
b) interdisciplinary research and education;
c) interdisciplinary research centers;
d) participation of undergraduates in research.

E2. In what way, if any, has the existence of the NSF ERC led to changes in university policies and practices?

E3. What issues, if any, have arisen before the faculty as a result of ERC activities?

F. UNIVERSITY TECHNOLOGY TRANSFER OFFICE

F1. Assess the impact of the ERC (or similar organized research units) on the importance of the following at your university:

a) team-based research and education;
b) interdisciplinary research and education;
c) interdisciplinary research centers;
d) engineering systems approach to research and education.

F2. To what extent, if any, have changes associated with any of the above affected your university's ability to

a) obtain industrial R&D funds;
b) leverage university funds to secure additional non-ERC research support;

c) transfer technology.

F3. What changes, if any, in university patent, licensing, or industrial liaison policies or organizational arrangements have occurred as a result of the ERC?

F4. What issues, if any, have arisen for your office as a result of the ERC's activities (or of those of similar organized research units)?

G. ERC ADMINISTRATIVE OFFICIAL

G1. Which, if any, university policies have constrained the effective operations of the ERC (e.g., budgeting, personnel, faculty appointments, indirect cost recovery)?

G2. Which, if any, university policies or practices have been changed as a result of activities generated by the ERC?

G3. To what extent are the ERC's administrative operating procedures being adopted by other units in the university?

G4. Which, if any, changes in university policies or practices proposed by the ERC have not been implemented? Why?

APPENDIX B
DATA TABLES

Enrollment Statistics for ERC Host Institutions

	Under-graduate Enrollment*	Graduate Enrollment*	Total Enrollment*	BAs Awarded Total**	BAs Awarded Engineering**	Percent BAs Engineering**	PhDs Awarded Total**	PhDs Awarded Engineering**	Percent PhDs Engineering**
Brigham Young University	30,037	2,694	32,731	7,194	353	5%	64	5	8%
Carnegie Mellon University	5,265	3,173	8,438	1,205	319	26%	152	67	44%
Columbia University	7,763	13,404	21,167	1,572	242	15%	461	36	8%
Duke University	6,368	5,443	11,811	1,599	199	12%	230	33	14%
Lehigh University	4,605	1,754	6,359	984	283	29%	83	39	47%
Massachusetts Institute of Technology	4,300	5,672	9,972	1,253	530	42%	475	227	48%
Mississippi State University	12,879	3,197	16,076	2,418	312	13%	128	10	8%
Montana State University, Bozeman	10,458	1,200	11,658	1,712	207	12%	32	2	6%
North Carolina State University	21,684	6,327	28,011	3,710	963	26%	316	66	21%
Ohio State University, Main Campus	36,092	11,911	48,003	6,746	544	8%	620	78	13%
Purdue University, Main Campus	32,526	6,945	39,471	5,470	1,069	20%	468	123	26%
Texas A&M University, College Station	36,082	7,735	43,817	7,512	980	13%	490	134	27%
University of Colorado, Boulder	22,976	5,875	28,851	4,734	390	8%	266	63	24%
University of Illinois, Champaign	28,916	9,935	38,851	6,370	1,001	16%	597	139	23%
University of Maryland, College Park	24,717	8,147	32,864	4,971	439	9%	461	80	17%
University of Minnesota, Twin Cities	32,342	13,019	45,361	4,880	637	13%	604	86	14%
University of Texas, Austin	37,159	11,850	49,009	7,826	789	10%	659	132	20%
University of Wisconsin, Madison	29,336	10,763	40,099	5,550	593	11%	729	105	14%

Source: National Center for Education Statistics, IPEDS College Opportunities On-Line, http://nces.ed.gov/ipeds/cool.

* Fall enrollment 1999, ** Conferred between July 1, 1999 and June 30, 2000

Rank Order of Effectiveness of Research-Doctorate Programs in Engineering

	Aerospace		Biomedical		Chemical		Civil		Electrical		Industrial		Materials Science		Mechanical	
	1982	1993	1982	1993	1982	1993	1982	1993	1982	1993	1982	1993	1982	1993	1982	1993
Brigham Young University					44.5	39.5		55.5		68						
Carnegie Mellon University					13	12	19	10	11	8				9	20	19
Massachusetts Institute of Technology		2		2	8	2.5	3	1	2	2				1	2	3
Mississippi State University									83.5	107						
Montana State University																108
Purdue University		9			15	15	9	11.5	7	10		4		41	7	7
Texas A&M University		19.5		33	51.5	41	20.5	23.5	64.5	27		10			56.5	26
University of Colorado		17			29	26	22	20	36	38						60
University of Maryland		19.5			48.5	45	40	32.5	17	18.5				56	34.5	39.5
Carnegie Mellon Design																
Columbia University					48.5	60	14	28	15	12				26.5	27	42
Duke University				12		90	34	30	45.5	58				50		33
Lehigh University					28	24	16	18		56		14		16	17	23
Ohio State University		23		22	32	30.5	26	35.5	20	16		12		19	27	24
North Carolina State University		21		34.5	30	25	26	29	44	23		11		22	33	27.5
University of Illinois		13			7	6	2	5	4	3		13		7	10	6
University of Minnesota		12		17	1	1	31.5	14	23.5	18.5				14	6	11
University of Texas - Austin		7		19	14	13	7.5	4	14	13				26.5	16	13.5
Total Number of Universities ranked		33		38	75	90	63	86	85	126		37		65	77	110

Sources: National Research Council (1995), *Research-Doctorate Programs in the United States,* Appendix Table I-3, pp. 220-226, Appendix Tables P-1, P-8, P-10, P-16, P-23, P-25, P-27; and National Research Council, An Assessment of Research-Doctorate Programs in the United States: Engineering .

Total University R&D Expenditures and Percentage from Industry
(Dollars in Thousands)

Institutions	Initial Year of ERC	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
ham Young University														
tal	1986	11,341	10,967	11,544	11,608	12,682	14,469	13,587	13,859	14,102	11,791e	11,502e	11,963	23,985
Rank		166	169	170	180	181	181	194	196	196	202	218	221	176
ustry		2,150	1,438	1,488	1,845	1,817	2,241	1,678	1,712	1,815	1,865i	n/a	n/a	2,781
Rank		104	145	150	147	150	142	164	166	161	162	n/a	n/a	142
Percent Industry		19.0%	13.1%	12.9%	15.9%	14.3%	15.5%	12.4%	12.4%	12.9%	15.8%	n/a	n/a	11.6%
egie Mellon University														
tal	1986/1990*	83,763	94,051	101,635	100,201	103,030	110,571	118,261	122,580	125,659	136,514	134,954	137,450	142,174
Rank		46	46	50	53	55	55	55	55	58	55	60	66	67
ustry		16,130	17,092	18,976	20,295	20,438	19,003	18,180	14,112	17,763	21,521	18,016	19,136	17,761
Rank		6	6	9	9	10	10	12	21	16	14	23	24	26
Percent Industry		19.3%	18.2%	18.7%	20.3%	19.8%	17.2%	15.4%	11.5%	14.1%	15.8%	13.3%	13.9%	12.5%
mbia University, Main Division														
tal	1985	149,904	160,976	172,145	182,769	194,666	199,516	204,710	236,417	244,991	236,403	244,337	267,007	279,587
Rank		19	19	23	21	23	24	24	20	21	25	27	26	26
ustry		3,915	4,841	5,408	5,618	6,619	6,454	5,919	1,632	1,478	2,559	1,637	3,018	2,630
Rank		62	55	55	63	60	65	73	171	183	139	170	132	146
Percent Industry		2.6%	3.0%	3.1%	3.1%	3.4%	3.2%	2.9%	0.7%	0.6%	1.1%	0.7%	1.1%	0.9%
e University														
tal	1987	89,556	113,968	131,090	140,708	164,232	188,678	202,434	220,220	218,703	242,235	251,536	282,388	348,274
Rank		42	34	30	31	27	26	25	25	26	23	25	22	17
ustry		8,085	12,379	12,551	12,252	22,876	31,977	34,572	30,241	32,560	42,797	48,178	65,114	121,630
Rank		24	12	16	19	7	3	3	4	4	3	3	1	1
Percent Industry		9.0%	10.9%	9.6%	8.7%	13.9%	16.9%	17.1%	13.7%	14.9%	17.7%	19.2%	23.1%	34.9%
gh University														
tal	1986	24,893	27,089	26,004	27,255	27,912	31,822	30,869	29,188	35,117	34,780	26,451	26,115	27,902
Rank		120	124	132	133	139	138	141	148	142	146	160	163	163
ustry		6,731	7,479	7,596	8,030	8,133	7,467	8,088	7,303	6,767	6,832	6,790	6,074	6,669
Rank		32	34	36	37	40	54	54	65	65	69	83	93	85
Percent Industry		27.0%	27.6%	29.2%	29.5%	29.1%	23.5%	26.2%	25.0%	19.3%	19.6%	25.7%	23.3%	23.9%
sachusetts Institute of Technology														
tal	1985	264,416	270,584	287,157	311,767	323,535	333,908	377,413	374,768	370,800	380,612	410,930	413,098	420,306
Rank		2	5	2	2	5	5	4	4	5	5	4	8	9
ustry		35,064	33,256	39,650	43,460	45,712	49,828	58,106	55,500	52,757	62,699	59,204	60,538	75,444
Rank		1	1	1	1	1	1	1	1	1	1	1	3	2
Percent Industry		13.3%	12.3%	13.8%	13.9%	14.1%	14.9%	15.4%	14.8%	14.2%	16.5%	14.4%	14.7%	17.9%

issippi State University														
tal	1990	40,405	45,005	53,670	58,492	64,335	65,754	70,300	76,201	72,145	84,124	84,157	100,410	110,8
Rank		96	95	93	96	95	96	94	92	104	89	96	86	86
lustry		2,823	3,430	3,886	6,389	7,163	6,920	6,012	5,913	6,165	7,599	5,469	7,470	7,89
Rank		89	79	81	55	51	59	71	79	71	63	93	77	71
Percent Industry		7.0%	7.6%	7.2%	10.9%	11.1%	10.5%	8.6%	7.8%	8.5%	9.0%	6.5%	7.4%	7.1
tana State University, Bozeman														
tal	1989	23,093i	25,227	25,968	27,648	30,278	34,419	32,911	36,149	47,998	50,097	49,440	52,292	55,4
Rank		129	128	133	132	132	133	136	136	95	122	125	127	12
lustry		2,454i	2,770	2,902	3,833	4,043	2,983	2,910	3,139	5,143	5,489	6,976	7378i	7,07
Rank		97	101	99	95	100	126	130	130	121	89	78	79	83
Percent Industry		10.7%	11.0%	11.2%	13.9%	13.4%	8.7%	8.8%	8.7%	10.7%	11.0%	14.1%	14.1%	12.8
h Carolina State University, Raleigh														
tal	1988	102,647	110,286	123,441	131,133	142,606	143,008	155,624	173,407	180,191	190,748	229,292	254,254	270,6
Rank		33	35	36	36	36	36	37	35	37	35	30	29	29
lustry		11,748	18,580	21,735	21,398	20,961	20,342	22,229	22,101	26,264	26,067	26,834	31,429	31,4
Rank		11	4	4	6	9	8	8	9	7	9	10	10	13
Percent Industry		11.4%	16.8%	17.6%	16.3%	14.7%	14.2%	14.3%	12.7%	14.6%	13.7%	11.7%	12.4%	11.6
State University														
tal	1986	123,246	154,652	173,485	178,569	194,919	203,291	221,460	230,515	246,287	262,147	289,100	301,518	322,8
Rank		26	23	22	23	22	23	23	21	19	19	17	20	19
lustry		9,278	10,910	20,244	14,744	15,409	13,994	13,647	14,883	21,827	30,870	36,685	40,401	52,0
Rank		21	17	7	15	14	17	17	16	13	7	6	5	5
Percent Industry		7.5%	7.1%	11.7%	8.3%	7.9%	6.9%	6.2%	6.5%	8.9%	11.8%	12.7%	13.4%	16.1
lue University														
tal	1985	107,131	118,797	124,323	130,379	136,325	140,260	149,032	172,733	203,419	206,951	206,588	216,479	226,4
Rank		30	29	34	37	38	39	40	37	32	33	34	37	38
lustry		9,579	10,325	11,451	11,632	11,962	12,607	13,174	21,639	25,147	25,720	26,090	26,988	28,8
Rank		19	19	19	24	23	23	22	10	10	10	11	14	16
Percent Industry		8.9%	8.7%	9.2%	8.9%	8.8%	9.0%	8.8%	12.5%	12.4%	12.4%	12.6%	12.5%	12.7
as A&M University														
tal	1989	219,853	231,161	250,706	272,800	288,005	305,390	322,691	355,750	362,539	366,983	366,798	393,720	402,2
Rank		8	8	8	8	8	8	7	5	6	7	9	10	11
lustry		13,398	18,534	21,204	26,197	23,050	28,675	27,182	28,576	31,452	26,947	31,816	33,674	34,7
Rank		9	5	6	4	6	4	6	5	5	8	7	8	9
Percent Industry		6.1%	8.0%	8.5%	9.6%	8.0%	9.4%	8.4%	8.0%	8.7%	7.3%	8.7%	8.6%	8.6

ersity of Colorado														
tal	1987	112,276	128,015	143,720	154,723	160,526	176,266	193,217	234,267	243,932	251,301	269,816	311,203	318,
Rank		28	28	28	29	30	28	27	24	18	21	21	17	2
lustry		4,502	5,234	6,728	7,426	8,251	10,655	12,218	13,312	7,607	8,902	9,403	9,963	9,8
Rank		54	48	41	43	38	32	27	25	28	56	53	59	6
Percent Industry		4.0%	4.1%	4.7%	4.8%	5.1%	6.0%	6.3%	5.7%	3.1%	3.5%	3.5%	3.2%	3.1
ersity of Illinois, Urbana														
tal	1986	188,682	197,393	210,590	225,634	243,380	251,970	252,811	245,407	246,174	268,995	286,470	338,841	358,
Rank		10	11	14	16	15	16	16	19	20	18	18	15	1
lustry		11,414	13,686	15,785	20,762	24,434	20,070	16,095	13,527	11,832	12,365	11,761	13,917	12,8
Rank		13	10	11	8	5	9	13	23	34	36	41	38	4
Percent Industry		6.0%	6.9%	7.5%	9.2%	10.0%	8.0%	6.4%	5.5%	4.8%	4.6%	4.1%	4.1%	3.6
ersity of Maryland, College Park														
tal	1985	126,239	135,531	149,510	166,022	206,432	219,041	229,344	198,348	209,945	216,957	215,927	223,190	257,
Rank		24	27	26	26	19	20	20	28	28	29	33	34	3
lustry		10,149i	11,451i	12,940i	14,229i	11,938	15,757	19,271	18,433	25,431	24,044	5,009	2,127	3,0
Rank		16	16	15	16	25	12	11	12	9	11	101	157	13
Percent Industry		8.0%	8.4%	8.7%	8.6%	5.8%	7.2%	8.4%	9.3%	12.1%	11.1%	2.3%	1.0%	1.2
ersity of Minnesota														
tal	1988	222,381	236,115	258,614	292,046	331,471	317,026	332,033	317,865	336,524	341,179	363,095	360,323	371,
Rank		7	7	7	7	3	6	6	9	9	9	10	14	1
lustry		11,056	10,670	12,389	18,086	19,270	17,529	21,524	23,726	23,427	23,726	24,196	24,094	23,
Rank		14	18	17	11	11	11	9	8	11	12	13	19	1
Percent Industry		5.0%	4.5%	4.8%	6.2%	5.8%	5.5%	6.5%	7.5%	7.0%	7.0%	6.7%	6.7%	6.4
ersity of Texas, Austin														
tal	1989	168,931	172,608	193,337	228,203	237,043	228,545	249,158	260,602	228,676	241,606	239,021	244,843	258,
Rank		16	17	17	15	16	17	17	17	24	24		30	3
lustry		3,161	3,175	2,694	3,507	5,734	4,814	4,106	4,268	3,257i	15,029	29,887	31,326	39,
Rank		78	87	105	101	73	87	109	105	122	25		11	7
Percent Industry		1.9%	1.8%	1.4%	1.5%	2.4%	2.1%	1.6%	1.6%	1.4%	6.2%	12.5%	12.8%	15.
ersity of Wisconsin, Madison														
tal	1988	254,493	271,418	285,982	309,841	326,489	352,706	372,362	392,718	403,541	412,570	419,810	443,695	462,
Rank		3	4	5	4	4	4	3	3	3	3	3	4	5
lustry		8,586	9,556	11,035	12,123	12,624	12,912	12,392	13,729	12,948	13,871	14,832	14,371	14,
Rank		22	20	21	21	18	22	25	22	29	28	30	35	3
Percent Industry		3.4%	3.5%	3.9%	3.9%	3.9%	3.7%	3.3%	3.5%	3.2%	3.4%	3.5%	3.2%	3.1

: i = imputed; e = estimated

gineering Design Research Center in 1986 and Data Storage Research Center in 1990

ce: Academic Research and Development Expenditures

'-1988, NSF 94-324, Tables B-32 (Total R&D) & B-38 (Industry-Sponsored R&D)

-1996, NSF 98-304, Tables B-32 (Total R&D) & B-38 (Industry-Sponsored R&D)

'-89 and 1991 ranks from WebCASPAR data runs, January 23, 2001

', NSF 99-336 and 1998, NSF 00-330, Tables B-32 (Total R&D) & B-38 (Industry-Sponsored R&D)

, Early Release Tables, Table B-32 (Total R&D) & B-38 (Industry-Sponsored R&D), online: http://www.nsf.gov/sbe/srs/srs01407/start.htm

ERC AUTM Data
(all dollars in thousands)

Institutions	Initial Year of ERC	1991	1992	1993	1994	1995	1996	1997	1998	1999
Brigham Young University	1986									
Licenses/Options Executed		8	20	11	12	19	25	11	14	21
Total Research Expenditures		15,100	18,500	11,174	11,687	11,544	15,419	11,779	12,795	17,227
License Income Received		689	608	568	1038	2,606	2,653	2,988	2,439	3,962
Income/Research Expenditure Ratio (x100)		4.5629	3.2865	5.0832	8.8817	22.5745	17.2060	25.3672	19.0621	22.9988
Invention Disclosures		18	14	15	24	23	31	30	38	71
Total Patents Applied For		8	9	6	5	5	8	13	15	12
Patents Issued		n/a	n/a	7	10	4	2	5	1	4
Start-Ups Initiated		n/a	n/a	n/a	3	2	2	3	2	1
Carnegie Mellon University	1986/1990*									
Licenses/Options Executed		n/a	n/a	8	14	17	10	14	11	23
Total Research Expenditures		n/a	n/a	146,730	150,705	151,978	164,983	165,844	169,900	167,675
License Income Received		n/a	n/a	546	1,507	1,441	7,135	13,381	30,065	5,892
Income/Research Expenditure Ratio (x100)		n/a	n/a	0.3721	1.0000	0.9482	4.3247	8.0684	17.6957	3.5139
Invention Disclosures		n/a	n/a	39	66	80	83	114	82	104
Total Patents Applied For		n/a	n/a	16	10	22	18	43	24	36
Patents Issued		n/a	n/a	6	6	5	8	4	14	30
Start-Ups Initiated		n/a	n/a	n/a	0	1	2	3	5	5
Columbia University, Main Division	1985									
Licenses/Options Executed		26	30	21	39	68	61	112	112	98
Total Research Expenditures		202,400	197,300	207,400	231,700	239,500	231,600	244,100	260,700	279,276
License Income Received		11,432	14,358	21,088	26,746	34,194	40,632	50,288	66,018	95,800
Income/Research Expenditure Ratio (x100)		5.6482	7.2772	10.1678	11.5434	14.2772	17.5440	20.6014	25.3234	34.3030
Invention Disclosures		310	310	290	298	339	300	285	151	182
Total Patents Applied For		17	18	44	53	138	94	111	85	109
Patents Issued		n/a	n/a	29	20	25	20	43	35	77
Start-Ups Initiated		n/a	n/a	n/a	1	0	1	4	5	5
Duke University	1987									
Licenses/Options Executed		25	31	27	25	22	n/a	38	49	41
Total Research Expenditures		140,000	160,000	189,202	206,880	203,455	n/a	360,977	282,000	334,506
License Income Received		887	654	641	1,556	1,790	n/a	1,520	1,319	1,600
Income/Research Expenditure Ratio (x100)		0.6336	0.4088	0.3388	0.7521	0.8798	n/a	0.4211	0.4677	0.4783
Invention Disclosures		57	89	85	98	95	n/a	146	112	115
Total Patents Applied For		33	50	86	73	139	n/a	69	87	111
Patents Issued		n/a	n/a	12	30	32	n/a	31	37	43
Start-Ups Initiated		n/a	n/a	n/a	0	1	n/a	0	1	2

Lehigh University	1986									
Licenses/Options Executed		n/a	n/a	n/a	4	3	1	0	3	n/a
Total Research Expenditures		n/a	n/a	n/a	18,719	19,402	34,391	25,146	23,243	25,312
License Income Received		n/a	n/a	n/a	85	123	131	113	187	218
Income/Research Expenditure Ratio (x100)		n/a	n/a	n/a	0.4541	0.6340	0.3809	0.4494	0.8045	0.8613
Invention Disclosures		n/a	n/a	n/a	25	28	15	14	6	n/a
Total Patents Applied For		n/a	n/a	n/a	13	13	13	16	13	n/a
Patents Issued		n/a	n/a	n/a	5	4	3	7	6	n/a
Start-Ups Initiated		n/a	n/a	n/a	3	0	0	0	0	n/a
Massachusetts Institute of Technology	1985									
Licenses/Options Executed		70	78	71	74	65	77	75	95	95
Total Research Expenditures		286,000	292,000	361,400	359,700	367,000	713,000	713,600	761,400	725,600
License Income Received		3,680	11,680	5,808	4,560	4,800	10,082	21,211	18,615	17,069
Income/Research Expenditure Ratio (x100)		1.2867	4.0000	1.6071	1.2677	1.3079	1.4140	2.9724	2.4448	2.3524
Invention Disclosures		240	291	282	280	260	338	360	356	381
Total Patents Applied For		155	143	161	203	258	158	292	372	341
Patents Issued		n/a	n/a	92	100	96	113	134	126	154
Start-Ups Initiated		n/a	n/a	n/a	22	13	6	17	19	17
Mississippi State University	1990									
Licenses/Options Executed		0	3	5	2	1	1	2	8	n/a
Total Research Expenditures		39,247	63,146	33,917	48,232	44,668	41,065	37,637	47,712	n/a
License Income Received		n/a	n/a	248	283	109	105	117	170	n/a
Income/Research Expenditure Ratio (x100)										
Invention Disclosures		2	18	17	12	18	17	15	21	n/a
Total Patents Applied For		0	1	6	4	20	30	42	9	n/a
Patents Issued		n/a	n/a	1	0	2	5	4	8	n/a
Start-Ups Initiated		n/a	n/a	n/a	0	1	0	2	1	n/a
Montana State University, Bozeman	1989									
Licenses/Options Executed		3	0	n/a	7	4	1	3	3	7
Total Research Expenditures		18985	24494	n/a	30,600	36,259	38,600	41,591	51,900	49,741
License Income Received		153	63	n/a	65	128	165	190	188	258
Income/Research Expenditure Ratio (x100)		0.8059	0.2572	n/a	0.2124	0.3530	0.4275	0.4568	0.3622	0.5187
Invention Disclosures		n/a	4	n/a	10	12	10	8	7	15
Total Patents Applied For		n/a	4	n/a	6	5	6	6	15	12
Patents Issued		n/a	n/a	n/a	3	3	3	7	1	7
Start-Ups Initiated		n/a	n/a	n/a	0	0	0	0	0	1
North Carolina State University, Raleigh	1988									
Licenses/Options Executed		15	16	33	39	26	n/a	54	39	83
Total Research Expenditures		69,486	89,549	122,734	261,754	292,564	n/a	334,394	379,856	413,369
License Income Received		818	1,101	1,543	1,632	1,823	n/a	3,165	4,281	7,761

Income/Research Expenditure Ratio (x100)		1.1772	1.2295	1.2572	0.6235	0.6231	n/a	0.9465	1.1270	1.8775
Invention Disclosures		76	75	75	86	108	n/a	105	101	148
Total Patents Applied For		27	42	61	51	45	n/a	48	48	62
Patents Issued		n/a	n/a	24	40	26	n/a	24	29	30
Start-Ups Initiated		n/a	n/a	n/a	1	3	n/a	1	5	8
Ohio State University	1986									
Licenses/Options Executed		16	30	20	21	32	12	14	16	26
Total Research Expenditures		154,000	164,000	144,915	197,200	213,500	207,734	205,400	209,686	257,950
License Income Received		1,600	1,200	1,109	1,122	1,276	1,097	2,233	1,759	1,626
Income/Research Expenditure Ratio (x100)		1.0390	0.7317	0.7653	0.5690	0.5977	0.5281	1.0871	0.8389	0.6304
Invention Disclosures		47	61	63	79	56	63	71	75	100
Total Patents Applied For		20	20	18	28	30	49	22	33	35
Patents Issued		n/a	n/a	21	9	13	21	27	24	18
Start-Ups Initiated		n/a	n/a	n/a	0	0	0	2	0	0
Purdue University	1985									
Licenses/Options Executed										
Total Research Expenditures										
License Income Received										
Income/Research Expenditure Ratio (x100)										
Invention Disclosures										
Total Patents Applied For										
Patents Issued										
Start-Ups Initiated					0	0	0	0	0	0
Texas A&M University	1989									
Licenses/Options Executed		n/a	n/a	27	33	36	30	35	54	53
Total Research Expenditures		n/a	n/a	322,691	355,750	362,539	366,983	366,798	393,720	402,203
License Income Received		n/a	n/a	796	1,502	1,730	2,756	4,081	4,467	5,262
Income/Research Expenditure Ratio (x100)		n/a	n/a	0.2467	0.4222	0.4772	0.7510	1.1126	1.1346	1.3083
Invention Disclosures		n/a	n/a	122	72	76	125	134	135	145
Total Patents Applied For		n/a	n/a	30	38	37	35	49	67	85
Patents Issued		n/a	n/a	24	24	21	19	21	21	19
Start-Ups Initiated		n/a	n/a	n/a	5	5	2	4	2	0

University of Colorado	1987									
Licenses/Options Executed		8	4	10	17	25	28	29	n/a	10
Total Research Expenditures		179,283	194,907	290,554	290,553	310,679	292,547	343,300	n/a	331,579
License Income Received		576	841	1,273	1,289	1,719	2,275	3,553	n/a	3,127
Income/Research Expenditure Ratio (x100)		0.3213	0.4315	0.4381	0.4436	0.5533	0.7777	1.0350	n/a	0.9431
Invention Disclosures		62	55	71	91	83	100	118	n/a	79
Total Patents Applied For		25	22	32	44	57	60	77	n/a	63
Patents Issued		n/a	n/a	16	13	17	24	21	n/a	27
Start-Ups Initiated		n/a	n/a	n/a	1	1	0	4	n/a	1
University of Illinois, Urbana	1986									
Licenses/Options Executed		6	33	37	60	68	n/a	n/a	34	39
Total Research Expenditures		167,096	174,485	252,811	245,407	246,174	267,008	286,470	338,841	358,247
License Income Received		268	563	856	1,438	3,112	3,087	4,380	3,121	2,896
Income/Research Expenditure Ratio (x100)		0.1604	0.3227	0.3386	0.5860	1.2641	1.1561	1.5290	0.9211	0.8084
Invention Disclosures		41	71	64	48	60	73	147	104	104
Total Patents Applied For		19	25	26	29	39	30	41	31	53
Patents Issued		n/a	n/a	10	18	18	17	20	23	14
Start-Ups Initiated		n/a	n/a	n/a	0	2	n/a	n/a	2	4
University of Maryland, College Park	1985									
Licenses/Options Executed		20	29	38	41	42	47	50	69	61
Total Research Expenditures		112,800	122,200	125,440	198,348	139,095	140,029	131,114	164,290	185,036
License Income Received		271	425	512	672	765	1,264	1,372	1,817	1,000
Income/Research Expenditure Ratio (x100)		0.2402	0.3478	0.4082	0.3388	0.5500	0.9027	1.0464	1.1060	0.5404
Invention Disclosures		55	62	72	73	74	75	92	102	84
Total Patents Applied For		11	14	20	27	28	41	87	145	113
Patents Issued		n/a	n/a	19	17	16	17	5	18	12
Start-Ups Initiated		n/a	n/a	n/a	1	1	0	0	2	3
University of Minnesota	1988									
Licenses/Options Executed		35	46	46	36	69	77	163	65	71
Total Research Expenditures		241,500	239,100	262,000	222,145	293,500	242,790	247,343	432,929	417,556
License Income Received		539	613	1,163	1,279	1,906	6,335	4,891	4,113	6,281
Income/Research Expenditure Ratio (x100)		0.2232	0.2564	0.4439	0.5758	0.6494	2.6093	1.9774	0.9500	1.5042
Invention Disclosures		170	149	122	136	201	159	148	144	219
Total Patents Applied For		65	52	61	63	105	71	130	102	99
Patents Issued		n/a	n/a	30	34	25	29	66	38	55
Start-Ups Initiated		n/a	n/a	n/a	4	6	2	6	8	5
ALL U.S. UNIVERSITIES										
Total Research Expenditures**		9,544,140	10,236,480	10,658,871	11,626,619	12,060,381	12,981,001	13,362,811	14,322,449	15,200,000
License Income Received		123,172	156,642	210,291	231,507	266,467	321,637	418,971	526,144	593,706
Income/Research Expenditure Ratio (x100)		1.29055	1.53023	1.97292	1.99118	2.20944	2.47775	3.13535	3.67356	3.90596

**('99 estimated)

* Engineering Design Research Center in 1986 and Data Storage Research Center in 1990

Source: *The AUTM Licensing Survey*, various years, Association of University Technology Managers, Inc.

Schools	Initial Year of ERC	Overall rank*	Reputation rank by academics*	Reputation rank by practicing engineers*	Research activity rank*/**	Engineering research funding
Brigham Young University	1986					
1989						
1990						
1991						
1992						
1993						
1994						
1995						
1996						
1997						
1998						
1999						
Carnegie Mellon University	1986/1990*					
1989		7	7	14	8	$33,000,000
1990		10	6	15	8	$37,600,000
1991		16	8	16	20	$28,100,000
1992		10	8	16	4	$63,866,000
1993		10	8	16	13	$57,300,000
1994		7	10	12	7	$75,200,000
1995		6	8	13	8	$78,551,000
1996		8	8	13	6	$81,000,000
1997		4	8	12	6	$86,500,000
1998		8	7	13	na	$92,800,000
1999		8	8	12	na	$88,500,000
Columbia University, Main Division	1985					
1989		21	25	29	15	$22,700,000
1990		na	na	na	na	na
1991		na	na	na	na	na
1992		27	25	32	na	$21,988,903
1993		41	23	27	na	$15,900,000
1994		23	25	24	27	$23,723,000
1995		24	21	21	33	$25,160,000
1996		26	22	21	na	$26,665,000
1997		29	25	25	34	$29,400,000
1998		29	27	33	na	$33,600,000
1999		31	26	64	na	$35,700,000
Duke University	1987					
1990		na	na	na	na	na
1991		na	na	na	na	na
1992		na	na	na	na	na
1992		29	29	36	na	$12,172,115
1993		33	27	32	na	$11,076,932
1994		35	25	32	na	$12,231,000
1995		33	28	29	na	$14,403,000
1996		35	27	37	na	$16,957,246
1997		32	25	35	53	$18,000,000
1998		33	27	33	na	$20,300,000
1999		33	26	33	na	$25,300,000

Lehigh University	1986					
1989		na	na	na	na	na
1990		na	na	na	na	na
1991		na	na	na	na	na
1992		33	39	29	na	$21,725,035
1993		35	34	22	na	$21,511,609
1994		39	40	22	na	$19,820,000
1995		42	37	28	na	$25,143,761
1996		37	38	30	na	$26,903,842
1997		43	42	38	36	$21,000,000
1998		40	43	32	na	$20,200,000
1999		40	45	29	na	$21,900,000
Massachusetts Institute of Technology	1985					
1989		1	1	1	3	$84,700,000
1990		1	1	1	3	$92,800,000
1991		1	1	1	1	$92,300,000
1992		1	1	1	1	$132,466,000
1993		1	1	1	1	$147,375,000
1994		1	1	1	1	$143,325,000
1995		1	1	1	1	$131,504,446
1996		1	1	1	1	$143,490,650
1997		1	1	1	1	$161,400,000
1998		1	1	1	na	$167,800,000
1999		1	1	1	na	$177,000,000
Mississippi State University	1990					
1989						
1990						
1991						
1992						
1993						
1994						
1995						
1996						
1997						
1998						
1999						
Montana State University	1989					
1989						
1990						
1991						
1992						
1993						
1994						
1995						
1996						
1997						
1998						
1999						

North Carolina State University, Raleigh	1988					
1989		na	na	na	na	na
1990		21	32	20	20	$34,500,000
1991		22	28	22	17	$43,300,000
1992		21	29	19	19	$40,593,970
1993		28	27	25	na	$43,315,012
1994		29	25	30	na	$45,200,394
1995		32	31	34	na	$47,179,397
1996		33	30	34	na	$51,678,425
1997		31	36	25	27	$56,600,000
1998		30	38	23	na	$62,000,000
1999		28	37	26	na	$66,700,000
Ohio State University	1986					
1989		20	20	16	27	$32,200,000
1990		12	15	15	10	$46,500,000
1991		11	16	15	9	$45,800,000
1992		15	18	9	17	$42,805,005
1993		19	16	11	20	$44,896,566
1994		18	20	15	18	$49,427,471
1995		20	21	18	18	$53,290,348
1996		22	18	13	21	$53,632,824
1997		25	25	18	21	$57,200,000
1998		20	22	15	na	$63,100,000
1999		22	22	18	na	$68,400,000
Purdue University	1985					
1989		11	9	2	23	$33,500,000
1990		7	9	2	15	$44,500,000
1991		5	9	2	10	$51,600,000
1992		5	8	4	7	$62,096,400
1993		3	9	2	4	$64,917,465
1994		10	7	4	11	$64,459,707
1995		10	10	6	12	$70,986,745
1996		10	10	7	8	$79,867,187
1997		8	10	3	8	$81,600,000
1998		9	10	4	na	$87,100,000
1999		9	10	3	na	$93,300,000
Texas A&M University	1989					
1989		12	23	13	7	$45,100,000
1990		18	24	13	13	$40,900,000
1991		13	22	10	11	$50,400,000
1992		14	18	12	14	$49,907,596
1993		20	23	15	18	$51,319,648
1994		17	20	16	8	$68,647,679
1995		17	21	17	4	$79,906,358
1996		18	22	24	3	$96,652,245
1997		21	22	17	4	$102,900,000
1998		14	18	18	na	$105,900,000
1999		13	18	15	na	$106,600,000

University of Colorado	1987					
1989		na	na	na	na	na
1990		na	na	na	na	na
1991		na	na	na	na	na
1992		42	25	33	na	$23,589,344
1993		22	27	37	28	$31,355,168
1994		26	25	27	na	$38,911,803
1995		30	31	32	na	$35,630,929
1996		30	30	24	na	$37,582,876
1997		35	33	27	40	$37,700,000
1998		33	31	31	na	$36,600,000
1999		30	33	22	na	$44,400,000
University of Illinois, Urbana	1986					
1989		3	4	6	4	$76,300,000
1990		3	3	3	5	$83,000,000
1991		3	3	4	3	$89,400,000
1992		3	2	5	6	$80,509,000
1993		4	3	7	10	$81,737,000
1994		3	1	7	10	$85,502,400
1995		4	5	7	10	$86,886,600
1996		3	2	5	10	$94,559,500
1997		4	6	3	9	$96,800,000
1998		6	5	5	na	$125,000,000
1999		6	5	8	na	$134,600,000
University of Maryland, College Park	1985					
1989		24	32	51	30	$21,300,000
1990		na	na	na	na	na
1991		na	na	na	na	na
1992		44	29	43	na	$29,173,000
1993		37	27	58	na	$31,963,674
1994		25	20	40	26	$43,880,744
1995		28	21	42	na	$62,096,264
1996		18	22	42	14	$69,728,878
1997		13	19	24	10	$75,500,000
1998		17	27	27	na	$86,900,000
1999		17	26	29	na	$92,000,000
University of Minnesota	1988					
1989		na	na	na	na	na
1990		na	na	na	na	na
1991		na	na	na	na	na
1992		23	14	17	81	$15,928,331
1993		15	14	20	16	$44,000,000
1994		14	14	20	17	$46,000,000
1995		12	15	16	22	$46,000,000
1996		29	15	16	na	$40,818,000
1997		18	16	16	30	$43,900,000
1998		20	15	17	na	$45,300,000
1999		23	14	19	na	$54,800,000

University of Texas, Austin	1989					
1989		8	13	10	6	$50,400,000
1990		8	11	9	6	$56,700,000
1991		8	11	14	5	$60,000,000
1992		8	8	10	8	$58,556,115
1993		9	9	14	7	$64,366,154
1994		8	10	10	9	$70,066,450
1995		11	10	14	13	$67,690,591
1996		11	10	18	12	$74,490,223
1997		11	12	10	10	$82,100,000
1998		10	10	9	na	$84,700,000
1999		9	10	11	na	$90,200,000
University of Wisconsin, Madison	1988					
1989		14	10	15	18	$35,400,000
1990		14	13	14	11	$42,800,000
1991		12	11	13	12	$46,100,000
1992		12	8	15	13	$52,449,700
1993		13	9	13	15	$59,657,000
1994		12	10	12	15	$62,338,850
1995		16	10	12	16	$60,961,900
1996		12	13	15	16	$64,506,579
1997		12	12	13	16	$70,400,000
1998		12	13	11	na	$70,200,000
1999		14	13	13	na	$69,700,000