POST-GRADUATION STATUS OF NATIONAL SCIENCE FOUNDATION ENGINEERING RESEARCH CENTERS

Report of a Survey of Graduated ERCs

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By

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DISCLAIMER

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Executive Summary

The National Science Foundation's (NSF's) Engineering Research Centers (ERC) Program stands as a landmark in successful federal support for university research and education in partnership with industry. NSF's policy for ERCs is that at the end of the ten- to eleven-year cooperative agreement,[1] NSF funding will cease and the centers are expected to become self-sustaining. They may recompete but there has to be a substantial and significant shift in the vision. This study is concerned with the experiences of the 33[2] 'graduated' centers and their survival as university research centers with ERC characteristics. It is based on two web-based questionnaires that were sent to the directors of all graduated centers and that elicited a response rate of well over 70%, as well as follow-up interviews and email correspondence with the directors and other center staff.

At the time of the study, most of the graduated ERCs continue to be successful as university research and education centers, with 82% (27) of them continuing to exist on campus as functioning centers with ERC-like characteristics. A substantial majority of the still-existing graduated centers continue to maintain most of the key characteristics of an ERC. Eighty to ninety percent of them continue to have the integration of research, education and industrial interaction as their general organizing principle and also to maintain an engineered systems focus, with the continued involvement of undergraduate as well as graduate students in collaborative, cross-disciplinary research. A somewhat smaller, but still substantial, number of centers (60 to 70%) continue to employ proof-of-concept test beds, have students involved in system-level activities, have strong industrial financial support and guiding direction, and have their university's commitment to the continuation of the center and center-related curriculum and degree programs. Sixty-seven percent of the centers that had instituted precollege programs[3] and 71% of the graduated ERCs that were established as multi-university collaborations continued them after graduation.[4] Of the centers that have moved away from embodying ERC characteristics, the most common changes are de-emphasized industrial involvement, increased single-investigator grants, less strategic planning, and reduced synergy between university departments.

Although there is a wide variation among the still-existing centers as to which of the key ERC characteristics were maintained after graduation, 23 (85%) of them continue to embody all the

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[1] ERC Program support for successful ERCs changed from 11 years to 10 years in FY 1998.

[2] As of January 2010. The total includes 30 graduated ERCs and 3 graduated Earthquake ERCs (EERCs).

[3] Pre-college programs were voluntary up to 2000. Many ERCs had proposed them before that or developed them during operation, but most of the earlier centers (Classes of 1985-88) did not have precollege programs.

[4] Beginning with the Class of 1996, multi-university collaborations became more common and soon universal.

primary characteristics that best define being an “ERC,” which are integration of research, education, and industrial interaction as their organizing principle and maintaining an engineered systems focus, with the continued involvement of undergraduate as well as graduate students in collaborative, cross-disciplinary research. Since this study is concerned not just with survival of ERCs as successful university research centers, but with their survival distinctly as ERCs, a key finding is that such a large percentage of the graduated ERCs continue to be self-sustaining with strong ERC characteristics.

Most of the graduated centers have not been as successful in maintaining funding at the levels received from the ERC program, with a few outstanding exceptions. Consequently, most of them have experienced downsizing and either the elimination or reduction of programs and infrastructure to address budgetary constraints. The majority of the centers continue to have substantial involvement of faculty, students, and staff researchers—although, as would be expected, their numbers have been reduced in most of the cases due to losses in funding. Most of the centers also continue to receive support and commitment from their home institutions, conduct effective education programs (albeit with reduced educational outreach activities), have strong support from their industrial partners, and continue to interact with industry through industrial advisory boards and formal membership agreements. For most of the centers, however, the number of industrial members has decreased since graduation and many have modified their approach to pursuing industrial involvement

Transition strategies have varied from center to center, with two-thirds of the centers deciding to continue as an unofficial ‘ERC’ after graduation. Marked differences in transition strategy can be seen between the centers in the earlier groups awarded (termed “year classes”) and later centers. Most of the earlier ones devoted considerable time and energy during the transition period to the process of applying for a new ERC award or an Industry/University Cooperative Research Centers (I/UCRC) grant. Interestingly, all of those centers that later disbanded are from the first four year classes, when recompeting for a new ERC was still a popular, but usually unsuccessful, transition strategy. Only three ERCs successfully recompeted for new awards and only one of them successfully completed a full second term of ERC support. Later graduating ERCs, however, realized the difficulty of successful ERC recompetition and/or realized that ERCs were not sustainable with I/UCRC grants and began thinking seriously about self-sufficiency somewhat earlier in the ten/eleven-year cycle. This transition was helped along by ERC funding policies which scaled back support in the last two years and ERC program requirements that all ERCs proposing a sixth-year renewal include a business plan for self-sufficiency.

Assessing the likelihood of transition success with key ERC characteristics intact retrospectively is a qualitative judgment based on impressions and observations and should be recognized as such. There are no “hot buttons” that correlate exclusively with success or failure, and the transition process is impacted by several factors. Most of the successful graduated ERCs, however, do share several factors in common that positively affect the transition process.

One of the factors positively impacting successful transition is concerned with who was involved in the development of a thoughtful transition plan. Most of the centers that had a successful transition had broad involvement of faculty, staff, industrial partners, and university administrators, which likely manifested itself in a sense of “ownership” and commitment among all of the stakeholders and was instrumental in the center’s ability to maintain adequate funding.

Another factor involves both the transition strategy and its implementation. Effective implementation of a realistic transition strategy that builds on and enhances the center's strengths, including having a research program that lends itself to a continued evolution at the forefront of its discipline, seems to correlate with sustainability. Institutional factors, such as the degree of university commitment to the ERC's survival, whether the center is visible and prized within the university, and whether general university policies are supportive of a cross-disciplinary approach to research and education, are also important to successful transition. In addition, it seems to be key that the center's education program—especially curriculum development and expansion—is sufficiently valued within the institution that it will be maintained. The most successful centers also had the commitment and interest of a core group of faculty who, despite the reduction in funding and number of faculty and the difficulties in maintaining buy-in because of the transition, saw the value of the center for obtaining funding and conducting research in a unique facility and with a cross-disciplinary focus. Support from industry during and after transition and the continuation of guidance from an industrial advisory board are other factors that seem to correlate with a center's likelihood of surviving. One apparent critical factor affecting self-sufficiency success that is difficult to isolate but seems to underpin many of the preceding factors is the quality of leadership of the management team. It not only involves the team's ability to define and navigate their evolving transition strategies, organizational structure changes, and operational needs, but also includes being able to inspire the confidence of the research team, the university, and industrial sponsors and ensure that the center effectively manages and meets the expectations of its funding partners.

The transition away from ERC Program support has ramifications broader than the decrease in available funding and the consequent downsizing that virtually all ERCs face without this baseline support.[5] Because NSF funding is fairly discretionary, centers use it to support the portions of their programs that are most difficult to fund otherwise. As a result, the effects of its loss is uneven across center activities and functions, with the most vulnerable post-ERC program elements generally thought to be basic fundamental research, center infrastructure, undergraduate student support, and outreach programs. The other type of loss associated with the absence of ERC Program funding is prestige. NSF ERC status is considered a major contributor to the prestige and standing of the universities and/or academic departments involved. Without it, there is not only the loss of much of the rationale for industry support through leveraging of NSF funding, but also the loss of status in the eyes of other potential new sponsors, including State governments. The NSF imprimatur reportedly makes a difference.

As noted, one of the major effects of the loss of NSF funding is the financial impact on the centers in trying to maintain their research and education programs. More than 80% of the graduated centers continue to experience reduced funding since graduation, while funding for the remainder has been stable, or in a few cases, actually increased. Current funding support for active graduated ERCs varies from center to center, ranging from reductions of as much as 90% ($0.3M current total) to increases as much as ten-fold ($50M current total). The mean total

[5] Average annual ERC Program funding for centers has of course varied across the 25-year history of the Program; but it has ranged from about $1.4M (in phase-down during the last two years) to over $4M, or from around one-third to one-half of a center's total funding.

current funding for the active graduated ERCs is around $6M, but the median is only about $2M, due to the large variations in funding levels. (See Figure 1 in report for details.)

The impact of the loss of NSF funding on the number of faculty, students, and staff researchers involved in center activities has varied considerably from center to center. Sixty-two percent of the graduated centers experienced reductions in the number of faculty involved, some with reductions of as much as 80%. Centers experiencing increases in the number of faculty reported increases of as much as 400%. Most of the centers also reported a reduction in the amount of student involvement since graduation. Seventy percent of the responding graduated centers have fewer undergraduate students involved, and 57% of them also experienced a reduction in the number of graduate students. The number of graduate students varies from a decrease of as much as 80% in some centers to an increase of as much as 300% in others, while the number of undergraduates ranges from a 90% decrease to a 600% increase, since graduation. This wide variability is often, but not always, correlated with the amount of decrease or increase in center funding.

The overall impact of the loss of NSF funding on the centers' education programs has likewise been inconsistent. Almost all of the centers continued to have graduate and undergraduate education programs post-NSF funding; only one reported phasing out their entire education program. A majority of the centers had planned to discontinue their outreach and pre-college education programs during transition planning to address anticipated budgetary constraints. Results are mixed for centers that did plan to maintain their outreach programs, with some continuing to operate successful Research Experiences for Undergraduates (REU) and precollege programs since graduation, while others have found it necessary to make significant reductions in these efforts.

Most of the centers that have continued to be successful have engaged in activities to increase the level and diversity of funding since graduation. These have included broadening funding sources to pursue State and private foundation funding, increased industrial collaboration, and increased funding from federal agencies, as well as becoming more aggressive and active in submitting proposals and identifying funding opportunities. Several centers also pursued increasing funding through higher industrial membership fees or broader membership; increased income from patents and spin-offs; increased user fees for laboratories, test beds, and facilities; and increased return of indirect cost recovery. The downsides of this additional effort are that the center leadership and core faculty have found it necessary to spend much more time on pursuing funding and less time on research and education as previously; and the majority of centers also reported an increase in short-term, more applied research projects as the reliance on industry funding increased.

Staffing changes over the years, due to budgetary concerns, has been one of the casualties of the graduation process, including impacts on center leadership that have varied considerably from center to center. Most of the centers no longer have education directors and several have combined the role of industrial liaison officer into other positions in the center. Many of them have also integrated their administrative and financial management activities into the university structure.

Two-thirds of the surviving centers reported that team orientation, the engineered-system focus, and interdepartmental collaboration were adversely impacted by the transition. Examples cited by several centers were that teams were smaller and that the systems approach was reduced. An equal number of them also reported changes in their overall field of research or industry since graduation, and as a result they have instituted new research programs and major thrust area changes.

A strong majority of the graduated ERCs reported that the program has had a long-term positive impact on the engineering research and education culture in their academic field, industry, and university, and almost all said that these culture changes have continued after NSF funding. Eighty-two percent of the centers reported having a long-term impact on their home institution; 77% felt they had positively impacted their academic field; and 60% reported impacting their industry partners. At least two of the graduated ERCs have been successful in attracting major industrial organizations to locate in their area because of the presence of the center.

The graduated ERCs have achieved an impressive body of advances in knowledge and technology and have been responsible for many major products and processes that have been commercialized by industry. These include well over a hundred start-up companies, a host of engineering software, materials developments, engineering designs, and numerous patents and technology licenses.

Most of the graduated centers question the ten- to eleven-year period of support as being arbitrary, and 75% of them thought that NSF's assumptions about their ability to attain self-sufficiency were overly optimistic. They note that some centers reach maturity early and then decline, while others are still working at the state of the art at ten or eleven years. Many felt that NSF hadn't adequately considered university politics—where, they say, external funding and the NSF stamp of approval are important drivers; or that industry's expectations often differ from NSF's. Their perception was that industry considers education programs as the responsibility of the university, and that although companies value longer-term fundamental research—which for the most part had been supported through the NSF funding—most of them are generally unwilling to support it. Interestingly, although a substantial majority felt that NSF's assumptions about self-sufficiency were flawed, 60% of them reported that a ten-year period is sufficient for a center to become established and to change the culture of engineering education and research in an academic institution. It is the sudden cessation of funding that they question.

Virtually all of the centers reported that the NSF ERC culture involving integration of research, education, and industrial interaction with a focus on cross-disciplinary, engineered systems research was extremely helpful in strengthening and sustaining the center before, during, and after graduation. Most felt that the cross-disciplinary engineered systems approach was key in making their research successful and provided them a competitive edge after graduation.

Although most of the graduated centers praised NSF's assistance in managing the transition process, several offered suggestions to help NSF facilitate the transition process and address the fact that even the most successful ERCs have difficulty retaining their ERC-like characteristics after NSF support ends. One recommendation is the development of some type of NSF-industry matching funding program for innovation that would reduce the risk of industry in utilizing new technologies developed by the ERCs. Other suggestions include having someone from the NSF staff or a previously graduated ERC provide assistance during the transition process to review progress and assess projections; having the NSF program manager/director provide more active assistance in this phase of the center's life cycle; or having the center maintain its involvement in the ERC program and the imprimatur of NSF through supplemental post-graduation funding for specific education or diversity outreach activities. An advantage of the latter suggestion is that it should increase the likelihood that centers, and their home universities, continue to think of themselves as part of the ERC family, maintain ERC-like characteristics, and have the status of NSF's stamp of approval—which in turn would likely have a positive impact on the center's ability to maintain and find additional support from other sources, especially federal agencies.

All of the graduated centers responding to the survey felt strongly that the effort involved in being an ERC was worth the benefits and results. Benefits reported include early development of leadership (for some of the centers, several department heads and deans had their start in the ERC); increasing the visibility of the university through collaborations with industry and other institutions; establishing multi-university collaborations that otherwise would have been impossible; and bringing a sea change to the university's attitude regarding multi-disciplinary efforts. They felt that the best aspects of life as an ERC included teaming and visionary projects that are beyond the capabilities of single investigators; NSF prestige; funding to provide flexibility to start projects quickly; a cross-disciplinary culture integrating research and education, a systems approach, and industry-orientation; and opportunities for collaboration with other departments, other institutions, and industry.

Despite their very positive responses to being an ERC, many of the centers also listed what they considered the worst aspects of life as an NSF ERC as having to deal with administrative setbacks due to department processes and politics, dealing with the burdensome amount of reporting and bureaucratic oversight, and the high pace of NSF interaction causing stressed-out faculty and center leadership.

In addition to experiencing the pros and cons of life as an NSF-funded ERC, the graduated centers also have had an opportunity to view life as a post-NSF center. They felt that the most gratifying aspect of having survived the transition process is the absence of NSF reporting, oversight, and micro-management. They saw the other benefits as being extensions of the culture that had begun when they were an NSF ERC and that had continued, and in many cases matured into fruition, in the post-graduation period. Graduating from NSF support obviously also created several difficulties for the centers. They listed the worst aspects of post-NSF life as a center as loss of NSF funds and prestige for leveraging other funding opportunities, having to constantly justify the center internally, the inability to continue to support educational outreach, a reduction in the number of companies willing to become members of the center, and (somewhat contradictorily) the absence of NSF attention in observing progress and helping to address difficulties. In reviewing what the centers felt were the best and worst aspects of being an ERC, both pre- and post-graduation, it is interesting that NSF oversight and guidance are seen as both a burden and a blessing.

Introduction and Background

This report describes the results of a study commissioned by the National Science Foundation (NSF) to evaluate the experiences of mature Engineering Research Centers (ERCs) after “graduation” from ERC Program and during their transition to self-sufficiency. It takes a look at their success in being self-sufficient, their progress once support from NSF was no longer available, the factors that contributed to their ability or inability to continue as successful cross-disciplinary research and education centers, and the impact of their approaches toward self-sufficiency on maintaining key ERC characteristics. Since NSF policy is based on the expectation that, by the end of the ERC cooperative agreement, centers will graduate from the program and become self-sustaining entities, NSF is very interested in the degree of success that ERCs have had in attaining this self-sufficiency, what might be done to further facilitate it, and NSF’s role in the graduated centers’ success in maintaining an ERC culture. This study is concerned not just with the survival of ERCs as university research centers, but with their survival distinctly as ERCs or ERC-like entities. The key questions are whether and to what extent critical programmatic characteristics of an ERC remain intact, and why they do or do not remain intact.

NFS’s ERC Program stands as a landmark in successful federal support for university research and education in partnership with industry. The goal of the program is to educate a globally competitive engineering workforce in an integrated, interdisciplinary research environment where academe and industry join in partnership to advance fundamental engineering knowledge and engineered systems. Since 1985, this partnership has produced a wide range of engineered systems and other technologies aimed at transforming product lines and industrial practices and processes, along with a new generation of graduates who have proven to be highly effective as technology leaders in industry. Today the program continues to expand and evolve to address national needs for the discovery and use of new knowledge and the education of a globally engaged, diverse, and highly capable engineering workforce.

The ERC mission has three main elements: (1) cross-disciplinary, systems-oriented research; (2) education and outreach; and (3) industrial collaboration and technology transfer. From their inception, the ERCs have embodied NSF’s strategic interests in the integration of research and education, in the integration of science and engineering disciplines, in partnerships between academe and industry, and in the improvement of science and engineering graduates’ ability to meet the nation’s needs in a global economy. In many ways, the program has redefined the concept of an academic research center, serving as a model for the development of other Centers programs in the U.S. and around the world.

Each ERC is established as a three-way partnership involving academe, industry, and NSF. While they differ from one another, all ERCs share the following key features:

- A long-term **strategic vision** for an emerging engineered system with the potential to spawn new industries or transform a current industry’s product lines, processes, service delivery, or infrastructure systems;

- A **strategic plan** that enables the ERC to realize its vision by delivering advances in knowledge, technology, and education and a diverse engineering workforce in academe and industry;
- A **research program** that integrates cross-disciplinary fundamental research with research to advance technology through proof-of-concept test beds designed to test theory in functioning systems;
- An **education program** that teams undergraduate and graduate students and integrates research results into curricula for pre-college and college students as well as practitioners;
- **Outreach in research and education** that enables a broad base of faculty, college-level undergraduate and graduate students, and pre-college students and their teachers to be involved in the ERC;
- **Partnership with industry** and other practitioners to formulate and evolve the strategic research plan, strengthen the research and education programs, and speed technology transfer; and
- **A diversity plan** that includes efforts to increase the diversity of the ERC's students and faculty at all levels to exceed national engineering-wide averages through active involvement of groups underrepresented in engineering.

Since the inception of the program in 1985 through 2009, NSF has awarded a total of 54 ERCs (including 3 Earthquake ERCs, or EERCs, managed by the ERC program but funded through other NSF funds), focusing on the broad technology areas of Bioengineering and Health Care; Energy, Sustainability, and Infrastructure; Manufacturing and Processing; and Microelectronics, Sensing and Information Technology. Fifteen of these centers are currently active in the ERC Program and 33 have graduated as mature ERCs. Figure 1 on page 13 illustrates the number of graduated and self-sustaining centers for each year class.

Previous Studies

Three similar self-sufficiency studies were conducted in the past. In 1997, NSF contracted with SRI International to explore the effects of graduation on centers. At that time, two ERCs had just graduated and five more had experienced the ramping down of NSF support that occurs in the last two years, so the report was predicting what the center management team expected would happen when funding was phased out. In general, the maturing centers downsized, with fewer students, less cross-disciplinary research, and fewer outreach efforts. Most new courses that had been introduced were being continued. The major impact of the reduction in NSF funding on education was seen in undergraduate research and outreach programs, which were discontinued. A follow-up study by SRI in 2000 of the five graduated ERC award cohorts, or "year classes" to date confirmed the findings of the first study. The centers had experienced downsizing, a shift in focus toward applied research, and decreases in student involvement and educational outreach.

SRI found that the self-sufficiency model that NSF initially assumed—sustainability with all or nearly all of NSF's defining ERC characteristics intact—was not an accurate reflection of the experience of most centers in the first five year classes and was flawed. While most centers continued to exist as financially viable entities, few appeared able to retain all or nearly all ERC-like characteristics once NSF base support came to an end. SRI concluded that the most successful transition occurred when the ERCs had the following features:

- Strong institutional support in a culture that fosters ERC-like characteristics;
- Motivated faculty, with institutional incentives that further that motivation;
- Strong commitment to the goals of ERC education programs;
- Research program that lends itself to a continued evolution at the forefront of its discipline.

Somewhat surprisingly, the results of this study also suggested that strong industrial support could actually work against a center's survival with ERC-like characteristics. While industry was said to value the longer-term, more fundamental research that for the most part was supported through NSF funding, the perception was that industry was generally unwilling to support it. As a result, most centers experienced an increase in short-term, more applied research projects and had trouble supporting infrastructure and educational activities with the direct funding generally provided by industry. Centers were also concerned about the impact of their no longer being able to leverage NSF funding on industrial consortia membership fees.

This second SRI 2000 report, which was written after the first four ERC year classes had recently graduated and the centers from the fifth year class were poised to graduate, went on to note that some centers seemed far more likely to survive, and with a greater retention of ERC-like characteristics, than did others. The report hypothesized some underlying variables that might have accounted for these differences, emphasizing that the measures of likelihood of transition success were a qualitative judgment based on impressions and observations during a center's move toward self-sufficiency, and should be seen as such. With that caveat, the hypothesized positive variables cited by SRI were: an ongoing supportive attitude from the university administration; high visibility and appreciation of the ERC within the larger university; university policies (such as promotion and tenure criteria and indirect cost recovery) that facilitate center-based research, faculty involvement and feelings of 'ownership'; educational components of sufficiently high perceived value to maintain faculty interest and student involvement; and effective transition planning. In addition, the specific research area in which the center was engaged, and especially one that was still fresh and evolving, also seemed to correlate with transition success.

A third study was conducted by NSF staff in 2005, but the information asked for was limited and most of the graduated centers did not respond. Of the eight graduated ERCs that responded, all but one received the majority of their support from sources other than university or industrial funding. The research of most of the responding graduated ERCs had migrated toward more industry-driven, applied research, much of which was an extension of their prior research. Despite this, most of them had been able to maintain an engineered system perspective in their research efforts and all of them continued to be engaged in some fundamental research. Loss of NSF funding was seen to have a deleterious impact on the center's educational and outreach efforts.

Survey Methodology

This current study was based on the responses to two web-based questionnaires that were sent to the directors of the 33 graduated ERCs. The decision to use two questionnaires resulted from suggestions made during a beta testing phase, in which the draft questionnaire was sent to three directors of graduated ERCs and selected NSF staff. The first web-based questionnaire was formatted to elicit the greatest possible response by framing the questions so that most of them could be answered fairly quickly (yes/no, multiple choice or brief responses). The first survey was followed with a second web-based questionnaire sent to those who indicated their willingness to provide additional explanation to allow the authors to gain deeper insight into the experiences of the graduated ERCs.

The survey for this study was successful in eliciting a response rate of well over 70%. Twenty-six of the 33 graduated ERCs responded to the initial questionnaire and 14 of 19 recipients responded to the longer follow-up questionnaire. Some of the responders chose not to answer all of the questions, so total responses varied somewhat from question to question. All of the graduated centers along with those whose input is included in this study are listed in Table 1.

In all but one case, the survey responder was the current center director and two-thirds of these were also the director during the transition process. Of the one-third who have assumed the director role since graduation, almost all were involved in the transition process and previously served the ERC in various roles, including deputy or associate director, thrust leader, industrial liaison, and/or faculty member. The responders also represented a broad cross-section of the graduated centers, including all four of the ERC technology clusters and every year class, ranging from the early years of the ERC program to the most recent graduates, and all had a substantial length of involvement with the ERC—20 for more than 5 years, and of these, 18 for more than 10 years.

General Overview of the Current Status of Graduated ERCs

Most of the 33 graduated ERCs continue to be successful as university research and education centers, with 82% (27) of them continuing to exist as functioning units on campus. Only six of the centers have disbanded following graduation from the ERC program. The reasons they cited for disbanding were lack of funding, internal pressures from their university to reduce the number of centers, a reversal by their university on a commitment to allow the center to benefit from the royalties being generated by ERC spin-off companies, and the reduction of semiconductor industry support for university research in silicon based materials and devices. Four of the active centers have morphed into larger consortia, institutes or university departments, which continue to be very successful. The center that created a new academic department reported they are in a gray zone; having built on the ERC legacy to launch a new undergraduate major, they find that differentiating between the contributions of center and department faculty can sometimes be difficult. Although they continue to be functioning units on campus, two of the active centers are significantly smaller than previously, having only one or two faculty.

The number of active and disbanded centers is broken down by year class in Figure 1. All of the centers that no longer function are in the first four year classes, specifically year class one, three, and four. Interestingly, year class two is the exception in that group, where all five of the graduated ERCs continue to be active. The reason that all of the disbanded centers seem to be grouped in the earlier year classes is not clear. Potential contributing factors include the unreliable transition strategy used by the first several year classes of reapplying for a new ERC, which was abandoned by later centers, or the fact that the passage of time has provided increased opportunity for faculty and university administrators to become enamored with newer, 'hotter' areas of research or for the center's technologies to become mature and no longer enhanced by university research efforts.

Table 1

Graduated NSF Engineering Research Centers

Color Key:
Blue = responded to initial survey only
Green = responded to both initial and follow-up survey
Red = did not respond to survey

Biotechnology and Health Care

- Duke University – Emerging Cardiovascular Technologies, 1987 to 1998 *(disbanded)*
- Georgia Tech – Engineering of Living Tissues, 1998 to 2008 *(still active)*
- Johns Hopkins University – Computer-Integrated Surgical Systems and Technology, 1998 to 2008 *(still active)*
- MIT – Bioprocess Engineering, 1985 to 1995 *(merged into follow-on ERC)*
- MIT – Biotechnology Process Engineering, 1995 to 2005 *(still active)*
- Montana State University – Biofilm Engineering, 1990 to 2001 *(still active)*
- Vanderbilt University – Bioengineering Educational Technologies, 1999 to 2007 *(still active)*
- University of Washington---Engineered Biomaterials, 1996 to 2007 *(still active)*

Design and Manufacturing

- University of Arizona – Environmentally Benign Semiconductor Manufacturing, 1996 to 2006 *(still active)*
- Carnegie Mellon University – Engineering Design, 1986 to 1997 *(still active)*
- Clemson University – Advanced Engineering of Fibers and Films *(still active)*
- University of Florida – Particle Engineering, 1994 to 2006 *(still active)*
- University of Maryland – Systems Research, 1985 & 1994 to 1997 *(still active)*
- University of Michigan – Reconfigurable Manufacturing Systems, 1996 to 2007 *(still active)*
- University of Minnesota – Interfacial Engineering, 1988 to 1999 *(still active)*
- Ohio State University – Net Shape Manufacturing, 1986 to 1997 *(still active)*
- Purdue University– Intelligent Manufacturing Systems, 1985 & 1994 to 2000 *(disbanded)*

Energy, Sustainability, and Infrastructure

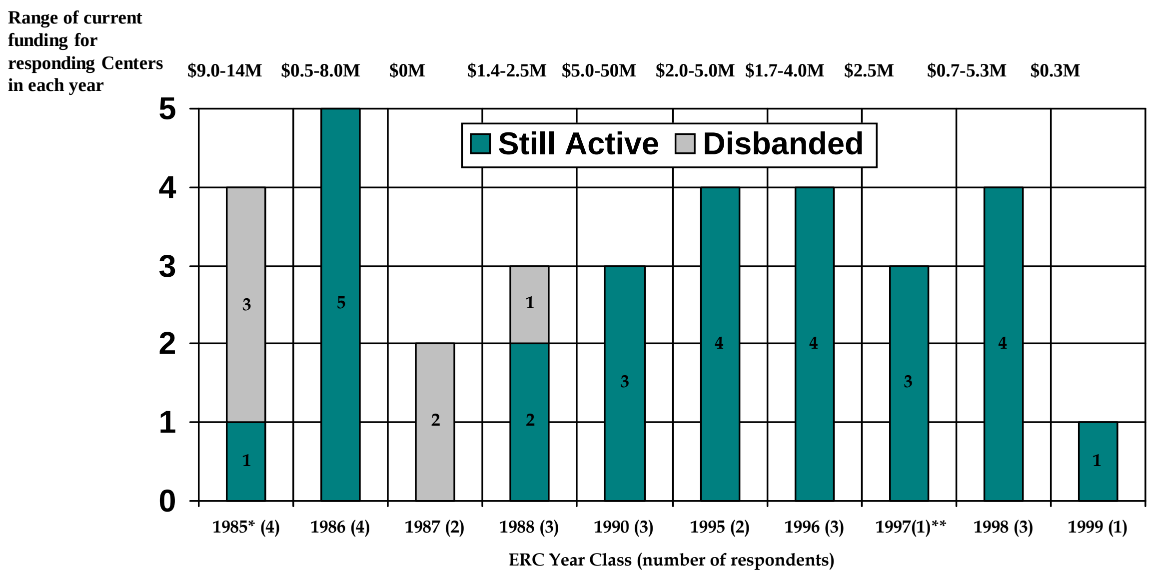
- Brigham Young University/University of Utah – Advanced Combustion Research, 1986 to 1997 *(still active)*
- University at Buffalo---Multidisciplinary Center for Earthquake Engineering Research, 1997 to 2007 *(still active)*
- University of California at Berkeley---Pacific Earthquake Engineering Research Center, 1997 to 2007 *(still active)*

- University of Illinois at Urbana-Champaign – Mid-America Earthquake Engineering Research, 1997 to 2007 *(still active)*
- Lehigh University – Advanced Technology for Large Structural Systems, 1986 to 1997 *(still active)*
- Texas A&M University of Texas – Offshore Technology, 1988 to 1999 *(still active)*

Micro/Optoelectronics, Sensing, and IT

- California Institute of Technology---Neuromorphic Systems Engineering, 1995 to 2005 *(still active)*
- Carnegie Mellon – Data Storage Systems, 1990 to 2001 *(still active)*
- University of Colorado – Optoelectronic Computing Systems, 1987 to 1998 *(disbanded)*
- Columbia University – Telecommunications, 1985 to 1996 *(disbanded)*
- Georgia Tech – Microelectronics Packaging, 1995 to 2006 *(still active)*
- University of Illinois---Compound Semiconductor Microelectronics, 1986 to 1997 *(still active)*
- Mississippi State – Computational Field Simulation, 1990 to 2001 *(still active)*
- North Carolina State – Advanced Electronic Materials Processing, 1988 to 1999 *(disbanded)*
- University of Southern California – Integrated Media Systems, 1996 to 2007 *(still active)*
- Virginia Polytechnic Institute---Power Electronics Systems, 1998 to 2008 *(still active)*

Figure 1
Self-Sustaining Graduated ERCs
Currently Self-Sustaining: 27 out of 33=82%

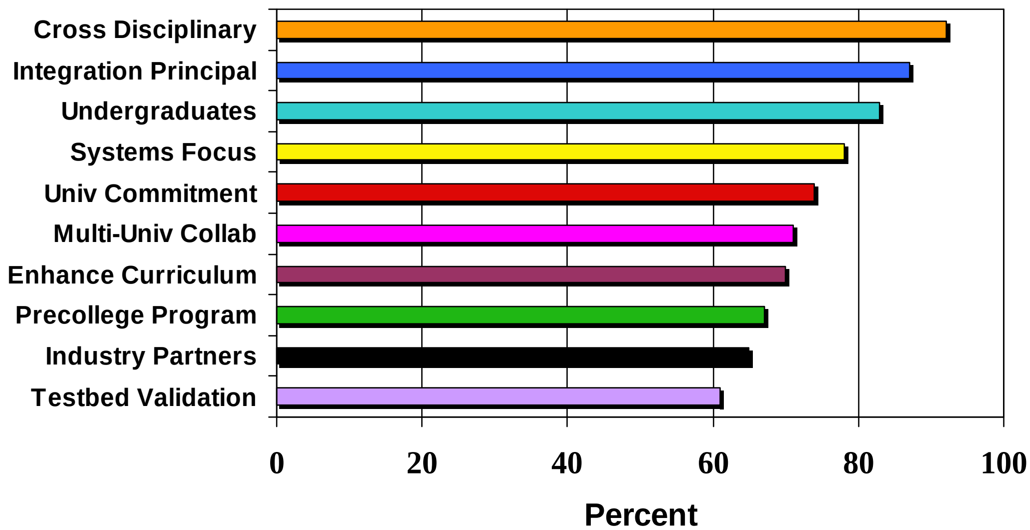


***Four Centers graduated. One remains active; four (4) responded to the survey.*

***Three Earthquake Engineering Research Centers were funded in 1997 with funds outside of the ERC Program but were managed by the ERC Program from 1999 through their graduation from NSF support.*

A substantial majority of the graduated centers have been successful in maintaining most of the key characteristics of an ERC (Figure 2). Eighty to ninety percent of them continue to have the integration of research, education and industrial interaction as their general organizing principle and maintain an engineered systems focus, with the continued involvement of undergraduate as well as graduate students in collaborative, cross-disciplinary research the integration of research. A somewhat smaller, but still substantial, number of centers, 60% to 70%, continue to employ proof-of-concept test beds, have students involved in system level activities, have strong industrial financial support and guiding direction and have a university commitment to the continuation of the center and center-related curriculum and degree programs. Sixty-seven percent of the centers that had instituted precollege programs and 71% of the ones that were established as multi-university collaborations continued them after graduation, Of the centers that have moved away from embodying ERC characteristics, changes have included de-emphasized industrial involvement, increased single-investigator grants, less strategic planning, and reduced synergism among university departments.

Figure 2
Key ERC Characteristics Still in Place



There is a wide variation among the still-existing graduated centers as to which of the key ERC characteristics were maintained after graduation, but 23 (85%) of them continue to embody the primary characteristics that best define being an "ERC," which are the integration of research, education, and industrial interaction as their organizing principle while maintaining an engineered systems focus, with the continued involvement of undergraduate as well as graduate students in collaborative, cross-disciplinary research. Since this study is concerned not just with survival of ERCs as successful university research centers, but with their survival distinctly as ERCs, it is notable that such a high percentage of the graduated ERCs continue to be self-sustaining with strong ERC characteristics.

Unfortunately, the graduated centers haven't been as successful in maintaining their funding. Consequently, most of them have experienced downsizing and either the elimination or reduction of programs and infrastructure to address budgetary constraints. The majority of the centers continue to have substantial involvement of faculty, students, and staff researchers—although, as would be expected, their numbers have been reduced in most of the cases due to losses in funding. The average numbers of personnel currently participating are outlined in Table 2. Both mean and median averages are included in this chart to provide additional clarity. These two averages differ quite a bit because of the impact of a few centers with very large numbers of faculty and students. Most of the centers also continue to receive support and commitment from their home institutions; conduct effective education programs (albeit with reduced educational outreach activities); have strong support from their industrial partners; and continue to interact with industry through industrial advisory boards and formal membership agreements.

Table 2
Average Faculty, Student and Research Staff Participation

Researchers	Mean Average	Mode Average
Faculty	26	13
Graduate Students	47	19
Undergraduate Students	40	10
Research Staff	17	9

Factors Affecting Successful Transition to Self-Sufficiency

Transition Strategies and Planning

Transition strategies have differed from center to center. The strategy of two-thirds of the ERCs at graduation was to continue as an "ERC" or ERC-like entity, while the other centers had decided to continue as something different after graduation. Seventy-five percent of the multi-university centers planned to continue collaborations with other researchers at partner institutions, with the center's lead university being in support of this in 100% of the cases.

Transition strategies for centers that planned to continue as something different included continuing as: part of a broader research group on campus; a multi-campus center focused on education; a broader, more diversified center pursuing new endeavors; a center focused on industrial/commercial support models; competing for a new ERC in a related area; an Industry/University Cooperative Research Center (I/UCRC); or a research unit with a large, long-term grant from a federal agency or industry consortium, such as SEMATECH or SRC, or a grant from NSF's Education Directorate or other sources to continue certain education functions.

Four of the graduated centers that decided not to continue as an 'ERC' had a transition strategy to form a larger Institute-type academic group in which the center would be one component. There are several benefits associated with this strategy, but there are also some potential disadvantages. In particular, research conducted under the umbrella of a larger group tends to be far more diffuse than within an ERC. In addition, the strategic planning process—which many centers reported as something they had come to value highly both as underpinning the cross-disciplinary relationships and keeping everyone working toward the same "vision"—tends to fall by the wayside in a broader institute-like environment. One of the centers that did successfully merge into a confederation of centers has worked to overcome these shortcomings through the formation of a university board to provide oversight and guidance.

Differences can be seen between the centers in the first two ERC year classes (1985 and 1986) and later centers in the transition strategies employed. Most of the centers in the first two year classes spent quite a bit of time in trying to obtain a new ERC award, thinking that there was a reasonably good chance of success; and indeed three of the ERCs in the first year class did successfully recompete. The downside was that this pursuit either delayed or diverted their attention from other self-sufficiency strategies, at least until late in their original ERC life span. ERCs from later year classes, however, having seen that none of the centers after the first year class received a new award and that NSF policy regarding recompetition had evolved to require that a new ERC have a new vision, began assuming that obtaining a new ERC award would be very difficult and started to pursue other transition strategies earlier in their life-cycle. This transition was helped along by ERC funding policies which scaled back support in the last two years and ERC program requirements that all ERCs proposing a sixth-year renewal include a business plan for self-sufficiency.

Another transition strategy for the first several year classes was to consider applying for an I/UCRC award. This approach, however, no longer seems to be considered as a serious strategy. Presumably the appropriateness of applying for these awards when many current I/UCRCs are trying to position themselves to become ERCs, or perhaps the administrative burdens associated with these relatively small awards, has made later centers rethink this part of their transition strategy.

In looking at the various transition strategies employed by the graduating ERCs, it's interesting to note the differences between the centers that appear to be the most successful in achieving self-sufficiency and financial stability and the ones that have either disbanded and/or have limited resources and thus a significant reduction in the number of faculty and students involved. The transition strategy for all but two of the ten centers that appear to be the most successful was to continue as an ERC. The two exceptions continued to maintain an ERC perspective but broadened their scope to encompass other related research areas on campus, in one case establishing a confederation of ERC-type centers. The most successful centers pursued either no or only limited shifts in their mission, scope, and programs in support of their transition plans—which for the most part focused on building on their previous successes, enhancing their existing areas of technology, and expanding their collaborations with industry and other federal agencies to obtain major grants in those technologies. Their approach required some fine-tuning in better defining the center's core technologies, making necessary staffing changes, and increasing focus on the present and future technologies relevant to their industry partners and selected federal agencies. In many ways, these centers continued to build on what they were best at, much like successful companies that work at exploiting their core technologies and avoiding diversion into areas that are not consistent with their strengths.

In contrast, only three of the eight centers that appear to have had the most difficulty in achieving self-sufficiency had a transition strategy to continue as an ERC. Five of them planned to continue as something different. These centers also saw significant shifts in mission, scope, staffing and programs that included downsizing, increases in contract and single-investigator research, undefined alternative funding sources, and the pursuit of new industrial support. One of the now self-sustaining ERCs started down this road and found it totally unproductive and returned to its core competencies and is now stable and self-sustaining.

Implementation of the Self-sufficiency Plan

Equally important with effective transition strategies and plans is effective implementation of the self-sufficiency plan. Some of the key actions in successfully implementing the transition plan for the ERCs included: obtaining financial assistance from the university; teaming with other ERCs to obtain funding from the state and other agencies; hiring a business development specialist to develop business and marketing plans; developing a business plan based on the research expertise of the center's faculty; broadening the scope of the research effort using the ERC-developed expertise to sustain the ERC model; focusing on increased support from industry using incentive and cost-sharing models; increasing revenue sources by charging fees for outside use of test beds and research facilities; expanding the research portfolio to enhance the center's ability to maintain funding support from industry and the university and obtain team-based, interdisciplinary research grants from Federal and State agencies; adopting the Fraünhofer model for technology transfer to enrich the ERC-style culture of the center; and, finally, extending the transition time-frame by saving industrial membership fees from the earlier years to use during the graduation process.

Assessing the factors that predict likelihood of transition success, as noted in the earlier studies on ERC self-sufficiency, is a qualitative judgment based on impressions and observations and should be recognized as such. This is because the transition process is impacted by several factors and there do not seem to be any "hot buttons" that correlate exclusively with success or failure. One additional complicating issue in assessing the likelihood of transition success is that information is limited regarding the less successful centers due to incomplete reporting. That said, most of the very successful graduated ERCs do have several factors in common, many of which are similar to the ones noted in the earlier reports (Table 3).

One of the factors positively impacting successful transition is concerned with who was involved in the development of a thoughtful transition plan. Most of the centers that had a successful transition had broad involvement of faculty, staff, industrial partners, and university administrators, which likely manifested itself in a sense of "ownership" and commitment among all of the stakeholders and was instrumental in the center's ability to maintain adequate funding. Another factor involves both the transition strategy and its implementation. Effective implementation of a realistic transition strategy that builds on and enhances the center's strengths, including having a research program that lends itself to a continued evolution at the forefront of its discipline, seems to correlate well with sustainability. Institutional factors, such as the degree of university commitment to the ERC's survival, whether the center is visible and prized within the university, and whether general university policies—tenure, promotion, space allocation, intellectual property, matching funds, equipment, and facilities support—are supportive of a cross-disciplinary approach to research and education, are also important to successful transition. In addition, it seems to be key that the center's education program is sufficiently valued within the institution that it will be maintained, especially with regard curriculum development and expansion. The most successful centers also had the commitment and interest of a core group of faculty who, despite the reduction in funding and number of faculty and the difficulties in maintaining buy-in because of the transition, saw the value of the center for obtaining funding and conducting cross-disciplinary research in a unique facility. Factors related to support from industry during and after transition and the continuation of guidance from an industrial advisory board are other factors that seem to correlate with a center's likelihood of surviving with key ERC characteristics. One apparent critical factor affecting self-sufficiency success that is difficult to isolate but seems to underpin much of the above is the quality of leadership of the management team. It not only involves the team's ability to define and navigate their evolving transition strategies, organizational structure changes, and operational needs; but also includes being able to inspire the confidence of the research team, the university, and industrial sponsors and to ensure that the center effectively manages and meets the expectations of its funding partners.

Table 3
Factors Affecting Successful Transition

- **Broad involvement of faculty, staff, industrial partners and university administration in transition planning**
- **Institutional factors---degree of university commitment, whether Center is prized and whether policies are supportive of cross-disciplinary research and education**
- **Education program sufficiently valued by faculty and students that it will be maintained**
- **Commitment and interest of core group of faculty**
- **Active industrial support and continuation of industrial membership and industrial advisory board guidance**
- **Effective implementation of a realistic transition strategy that builds on and enhances the center's strengths**
- **Quality of leadership of the management team**

Most of the self-sustaining centers report that they have had to face several challenges to sustainability. These varied from center to center, but most of the challenges seemed to focus on a few major areas. Of course, the principle one was being able to obtain enough external funding to sustain the core functions of the center and the interest of the faculty; but others included maintaining support from the university and negotiating sufficient space for labs and test beds, continuing effective multi-campus collaborations, establishing the synergistic relationships between different academic departments required to implement any new directions or thrusts, and adjusting the scope of the center and making the required organizational changes to match emerging needs and funding opportunities. An interesting challenge faced by some of the centers was in the "management of success," where successful research thrusts with strong leaders were now evolving into a new mode of operation requiring different synergisms.

Specific shifts in mission, scope, staffing, and programs that were anticipated or even planned by most ERCs during the transition process were reductions in support staff, a pull-back in the number of education programs, a broadened scope to encompass related technology areas on campus, reorganization into better-defined areas of technology, use of an I/UCRC model[6] for maintaining industrial partners, and increased focus on materials rather than processes for solid state electronics. Some of the shifts in emphasis regarding industry during the transition planning process included an increased focus on near-term and industry-driven research, a better-defined technical focus, an increase in the number of individual principal investigator projects, less systems focus, a reduction in overall research staffing, and an increase in the emphasis on technology transfer. At the time of graduation, most of the ERCs planned to continue center-related curriculum development as part of their education initiative; very few planned to pursue new degree programs and two-thirds of the centers planned to disband their REU, precollege, RET, and outreach programs due to budgetary constraints. Many reported that they had decided to scale back everything except graduate education because the lack of resources made it very difficult to continue a coherent, well-staffed education and outreach program.

Other Factors in Successful Transition

To better understand the factors related to successful transition exhibited by the graduated ERCs in this study, it will be helpful to examine some of them in more detail. For the centers that continue to be functional units on campus, 96% of them had faculty involvement in their transition planning, 60% had ERC staff involvement, 64% had the involvement of their industrial partners, and 72% involved the university administration. It's worth noting that these centers also experienced the least reduction in annual funding, and several of them actually saw an increase in funding. About half of the ERCs started transition planning in Year 6 or before, but an equal number waited until closer to graduation. In fact, more than one-third of the centers waited until the last two or three years of funding before addressing the issue of self-sufficiency.[7] One of the continuing graduated ERCs delayed their focus on self-sufficiency until they demonstrated success as an ERC and were able, based on their ERC-developed expertise, to provide the leadership, shared infrastructure, and ERC-type synergistic operational model to successfully take responsibility for related, but independent, research activities on campus at the prompting of university administration.

The continued commitment of the home universities to the graduated centers, which has been shown to be one of the factors impacting sustainability, has ranged from a high level of continued financial support for a specified number of years to help the graduated center achieve self-sufficiency, for most, to almost complete lack of interest in whether the center continued to exist at all for a few. The majority of the successfully continuing centers, however, reported that their university's policies have been supportive of an ERC culture and that the home institutions have shown strong commitment to their survival during the transition process. These centers received transition funding and continued support from the university in the range of $50K to $1M per year. Financial assistance ranged from direct cash contributions, to equipment

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[6] The I/UCRC model of industrial interaction is project-based, where firms vote on the industrial relevance of projects proposed by the center's team of faculty.

[7] Starting in the mid 1990's the ERC Program's reporting guidelines have required sixth-year renewal proposals to include self-sufficiency business plans that are reviewed annual thereafter by the NSF site visit teams.

donations, to allocation of research facilities, to administration staff and seed funding support, to graduate student support through waivers and fellowships, to allowing the center to retain all or part of the indirect cost recovery associated with all or some of its research grants, to cost sharing on new proposals put out by the center.

In addition to providing financial support, 88% of the continuing centers reported that the policies of their university regarding intellectual property and contract negotiation have been supportive of a continued ERC culture and 83% of these centers feel that they have adequate equipment and facility support from their home institution. Almost all of the centers also report that their university is supportive of a cross-disciplinary approach to research and education and that there are no or limited pressures on center personnel to do budgeting and/or publication along disciplinary lines. In fact, some centers have noted that they have had a positive influence on their university in modifying some of the policies and establishing a multidisciplinary research mindset leading to changes in promotion and publication guidelines to recognize the value of interdisciplinary research and education—a sweeping "culture change" of the kind originally envisioned by the ERC Program. Despite these successes, some centers reported that department heads and deans continue to focus on individual accomplishments, and that increasing budgetary stress on university departments has caused continued pressures for them to revert to traditional academic norms to show their own value and impact, independent of cross-disciplinary centers.

Despite an overwhelming majority of faculty being involved in the planning, 57% percent of the centers experienced difficulties in maintaining faculty buy-in during the transition process. Many of the faculty were reported to have lost interest and commitment when the opportunities for major blocks of funding were reduced, and in some cases existing funding became very specific and required expertise not embodied by the existing faculty; but in general, core faculty who saw the value of the center for funding and unique research opportunities continued to participate. Other factors negatively impacting faculty buy-in included the desire to pursue new areas of research, continued refocusing of the post-graduate research program, and recognition issues. In addition, some academic faculty had negative perceptions of the type of research that would now be funded more heavily by industry and how it would be valued by the university.

Industrial partners were very supportive of the ERC during the transition process and the immediate post-graduation period in almost 70% of the cases. An additional 17% were somewhat supportive and only three of the ERCs reported receiving either limited or no support from their industrial base. This may be at least partially because most of the centers had strong industrial involvement in establishing the transition plans, which ultimately had a strong industrial focus, along with industry's acceptance of a new, broader vision involving other companies with a wider range of needs. Some of the industrial components of the plan included the pursuit of increased industry funding by encouraging continued support by existing members, recruitment of new members in concert with existing members, industry-targeted precompetitive research projects, increased use of test beds and fee-based testing services, increased emphasis on the development of intellectual property to spawn new start-ups, and increased industry input into the motivation and planning of research projects.

Several of the centers did report experiencing significant changes in the nature of the industry in their field of research and in the types of research needed. One weathered a staggering industry consolidation resulting in an 80% reduction in the number of potential sponsors and a transition in the basic technology paradigm employed by the industry, and yet managed to continue as a very successful research and education university center. Others have experienced industry moving off-shore, a major economic recession, an industry focus on single-discipline research, and a reduction in the need for university research support as more and more of the center graduates are placed in industry. Adjustments have included expanding membership to non-U.S. companies, developing closer partnerships with industrial sponsors to gain an improved understanding of their needs, encouraging industrial use of ERC test beds and testing facilities, and expanding the center's technology focus to increase the range of industrial and government agency supporters. Those ERCs that have interacted with the automotive industry and the associated machine tool manufacturers have had to weather the constantly changing circumstances of recent years that have been difficult to respond to effectively.

Impacts of Loss of NSF ERC Funding and Status

More than 80% of all the graduated centers reported reduced funding after graduation, while funding for the remainder was stable, or in a few cases, actually increased. If the centers that disbanded at some point after graduation are not considered, the percentage that experienced funding reductions is slightly less, at more than 70%. As Figure 1 showed, funding support for these active graduated ERCs varies from center to center, ranging from decreases of as much as 90% ($0.3M current total) to increases that are as much as ten-fold ($50M current total). The mean total current funding for the graduated ERCs is around $6M, but the median is only about $2M due to the large variation in funding levels. To put these numbers in context, average annual ERC Program funding for centers has varied across the 25-year history of the program; but it has ranged from about $1.4M in the phase-down period during the last two years of NSF support to over $4M per year, or from around one-third to over one-half of a center's total funding.

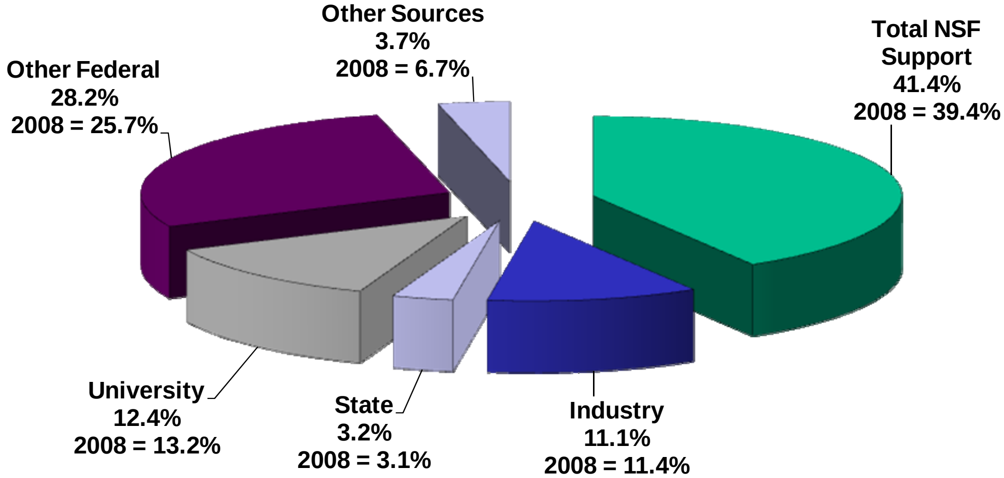
The transition away from ERC Program support has ramifications broader than the decrease in available funding and the consequent downsizing that virtually all ERCs face without this baseline support. For one, the nature of the ERC support compared with funding from other sources means that the effects of its loss will be uneven across center activities and functions. The ERCs' use of NSF funding has been fairly discretionary, with centers generally using it to support portions of their programs that were more difficult to support otherwise, such as fundamental, higher-risk, longer-term research; support for graduate and undergraduate participation in center research teams; and costs associated with center infrastructure, both in terms of technicians/maintenance of equipment and facilities and administrative personnel. As a result, these elements became the most vulnerable with the loss of NSF support. Few individual PI awards cover the type of cross-disciplinary, fundamental research typical of ERCs and the sum of such awards, even if interdisciplinary, would not make up the deficit in the entire ERC's fundamental research effort; also, the perception is that while industry values the fundamental research, it will not generally support it. In addition, few government grants or contracts provide support for infrastructure, undergraduate education, and outreach, and certainly not at the level enabled by the ERC Program funds. While faculty were thought likely to be able to continue to support some students, the ability to maintain the cross-disciplinary, team-based efforts was questioned.

Most of the centers that have continued to be successful have engaged in activities to increase the level and diversity of funding since graduation. These have included broadening funding sources to pursue state funding, increased industrial collaboration, and increased funding from federal agencies and becoming more aggressive and active in submitting proposals and identifying funding opportunities. Several centers also pursued increasing the amount of funding through: higher industrial membership fees, cost-shared research projects, or broader membership, including accepting more foreign firms as members; increased income from patents and spin-offs; increased user fees for laboratories, test beds, and facilities; and increased return of indirect cost recovery. The downsides of this additional effort are that the center leadership and core faculty have found it necessary to spend much more time on pursuing funding and less time on research and education than previously; also, the majority of centers reported an increase in short-term, more applied research projects as the reliance on industry funding increased.

A factor complicating the effort to expand center funding is that the loss of ERC Program support brings with it a loss of prestige. NSF ERC status was considered a major contributor to the prestige and standing of the university and/or academic departments involved. Without it, there is not only the loss of much of the rationale for industry support through leveraging of NSF funding, but also the reduced status in the eyes of other potential new sponsors, including the state government. The NSF label reportedly makes a difference. Over time, industry has learned to accept the center's eventual loss of NSF funding, but is often still puzzled by it. They ask: if the research is of high quality and producing valuable results, then why is NSF abandoning it? In some cases, this makes it more difficult for industry representatives to justify their expenditure on continued membership in the ERC.

Figure 3 shows the breakdown of funding for current ERCs by source for FY2009. Similar data for the graduated centers is limited but suggests, for the centers where total support has either remained stable or increased since becoming self-sufficient, that the loss of NSF funding that previously accounted for about 40% of their budget has been offset by the other major funding sources. Industry, non-NSF Federal, State, and university sources are now playing a much stronger role in providing financial support to these centers.

Figure 3
Total Current ERC Support -- FY 2009 (21 ERCs)



Total value of support: $160.1 million

Staffing changes over the years due to smaller budgets has been one of the casualties of the graduation process, including a wide range of impacts on center leadership that have varied considerably from center to center. Even though two-thirds of the centers have managed to retain their deputy director and administrative manager positions, many no longer have industrial liaison officers, and 60% of the centers have eliminated the education program director position. Also, in many of the cases, even though the leadership positions have retained titles and strategic roles, they have less authority as the financial, business, and administrative aspects of the center have been consolidated and/or integrated into the university structure and shared with the departments or college.

The impact of the loss of NSF funding on the number of faculty, students, and staff researchers involved in center activities also has varied considerably from center to center, with some existing graduated centers experiencing decreases and others increases. If all of the responding graduated centers are included, 62% of them have seen a reduction in the number of faculty involved, with some centers reporting decreases of as much as 80% while others report increases of up to 400%. The percentage of centers that have experienced faculty reductions changes quite a bit, to 47%, if the centers that disbanded after graduation are not considered. For many of the centers, as the number of academic faculty has decreased, the number of research faculty, staff researchers, and post-docs has increased to at least partially offset the reduction. In addition to experiencing a reduction in the number of faculty, the majority of the centers also reported a broadening of the disciplinary composition of the faculty currently involved.

As indicated in the earlier studies, most of the centers also reported a decrease in the amount of student involvement since graduation. However, this may not have been as pervasive as the earlier studies suggested. Seventy percent of the responding graduated centers have fewer undergraduate students involved, and 57% of them also experienced a reduction in the number of graduate students. These reductions change to 57% and 40%, respectively, if the centers that disbanded since graduation are not considered. The actual number of graduate students varies from a decrease of as much as 80% in some centers to an increase of as much as 300% in others, while the number of undergraduates ranges from a 90% decrease to a 600% increase, since graduation.

The majority of the self-sustaining centers have also experienced a decrease in the number of industrial members and many have modified their approach to industrial involvement. A substantial majority of the centers continue to receive guidance from an industrial advisory board and operate with a center-wide industrial membership and intellectual property agreement. Most of the advisory boards, however, have seen changes since graduation, including a transition from using a member-based model to a project-by-project sponsored research model, flexible membership fees based on research scope, expanded membership options and increased focus on larger companies. For a few of the centers, industrial benefits regarding access to intellectual property have also been modified. Most of the graduated ERCs continue to collaborate with industry on research projects in the same way as before, but a few have seen a broader participation and increased dialogue on project suitability. Despite the shorter-term perspective (or perhaps because of it), more than 70% of the centers have reported an increase in technology transfers and patent filings and licenses to industry. One factor contributing to this also could be the late maturation of developments begun as early-stage fundamental research inquiries under NSF funding.

Two-thirds of the centers reported that team-orientation, the engineered system focus, and interdepartmental collaboration were adversely impacted by the transition. Examples cited by several centers were that teams had become smaller and that the center-wide systems approach was weakened. Despite the shorter-term focus, only a few of the graduated centers actually experienced a reduction in cross-disciplinary, fundamental research and enabling technology development, and 57% of the centers said that their research thrusts continued to be as interdependent as they were when they were an NSF-funded ERC. In those minority cases where once interdependent thrusts have become independent, examples included strong thrusts that evolved into their own centers or independent activities and areas where a natural maturing resulted in increased individual faculty responsibility for obtaining funding.

Seventy-two percent of the surviving centers reported changes in their overall field of research or industry since graduation, and most of them found that the changes actually made the transition process easier. Changes cited included shifts from commodity to high-value-added materials that benefited graduated ERC test beds and testing facilities and the maturation of research areas into more diverse activities involving new strategic thrusts and basic research. As a result of these changes in their overall field of research, over 80% of the centers have instituted new research programs, and about half have experienced major thrust area changes. Responses have also included expanded thrust areas, more focused and strategic research activities, broadened research objectives, and in some cases, increased sensitivity to local and national agendas. Increased collaborative research activities with industrial consortia or other academic institutions have also been reported by several of the graduated centers. For example, two of the centers have joined together to collectively address government funded research activities in their state; two others have collaborate to address federally funded societal issues; one has worked with a number of other universities; and two others are conducting collaborative research as part of government agency contracts with industry and academia.

The graduated centers reported that their research programs have achieved a wide range of significant advances in knowledge and technology since they have been self-sufficient. A few key advances are cited in Table 4.

Table 4
Significant Advances in Knowledge and Technology Achieved by Centers Since Graduation from NSF Support

- **Design of hybrid communication networks (satellite/wireless/wireline)**
- **Biochemical sensing system design and development for toxin detection.**
- **Medical control of targeting tumor therapies**
- **Key understanding of next-generation heat assisted magnetic recording to position it as the leading candidate for next-generation recording**
- **Invented and developed microwave assisted magnetic recording for future applications**
- **Widespread adoption in government and industry of ERC developed modeling technology**
- **New hurricane forecasting capabilities based on novel combinations of remote sensing datastreams**
- **High fidelity, digital human modeling that embraces physical motion and cognitive behavior**
- **High performance steel for infrastructure applications and use in highway bridges**
- **Next-generation engineering systems designs, blending fundamental research with research focused on technological advancement**
- **Advances in high K gate dielectrics, metal gates and Si/Ge contacts for nanometer CMOS devices**

The impact of the loss of NSF funding on the centers' education programs has been inconsistent. Almost all of the centers continued to have successful graduate and undergraduate education programs post-NSF funding, many with reduced enrollment, and only one reported phasing out their entire education program. A majority of the centers had planned to discontinue their outreach and pre-college education programs during transition planning. Results are mixed for centers that did plan to maintain their outreach programs, with some continuing to operate successful REU and precollege programs since graduation, while others have found it necessary to make significant reductions in these efforts. A continuing strong commitment to education in ERC-related areas and inherent strengths in pre-college and outreach education that remained active after graduation have been cited by the centers with successful outreach programs. The centers that reduced their education programs cited lack of funding, lack of NSF involvement, and limited faculty interest as the drivers. One center commented that the reduction in graduate and undergraduate education efforts was consistent with the goals of their current funding sources and faculty interest and that outreach and pre-college efforts were not considered a high priority. Consistent with their reduction in educational outreach, half of the graduated ERCs decided to discontinue special programs to recruit women and minorities after the center's graduation. It should be noted that NSF has recently placed greater emphasis on supporting these programs and requiring strategic diversity planning, so ERCs graduating after these centers might show different results.

Changes in education programs since graduation do not seem to have had a deleterious effect on the interaction between students and the center's industrial partners. In fact, if anything, most such interactions have increased with the increasing reliance on industrial funding. Activities such as student internships with industry, visiting industrial researchers, industry personnel serving on PhD committees, and student hiring continue to be strong and in most cases have been enhanced since graduation.

In contrast to the lack of emphasis on educational outreach, but consistent with the increased focus on research, graduated ERCs have continued their information dissemination and professional outreach efforts. Over 90% of them have initiated regular workshops on center-related technology advances and more than 80% provide regular seminars in these areas. Several of them have also received awards, recognition, and press coverage for their educational efforts. These recognitions include multi-institution education grants, best paper awards, IEEE education awards, and industrial graduate student fellowships.

Long-Term Impact of the ERCs

A strong majority of the graduated ERCs have seen a lasting positive effect of the ERC approach on the engineering research and education culture in their academic field, industry, and university; and almost 90% said that these culture changes have continued after NSF funding ended. Eighty-two percent of the centers reported having a long-term impact on their home institution; 77% felt they had positively impacted their academic field; and 60% reported impacting the way their industry partners operate. To stay in touch with the careers of their graduates and their individual impacts in industry or academia, most of the centers keep track of former students through technical conference receptions, invitations to participate in center activities, updated mailing lists, and personal interactions. Most graduated ERCs report that their graduates have assumed key research and executive leadership positions in member companies.

One of the primary drivers for the establishment of the Engineering Research Centers Program was to facilitate the transfer of knowledge and technology developed out of the ERCs' research on next-generation and even transformative engineered systems into U.S. industry. This focus on innovation was and still is at the heart of the ERC-industry partnership. This partnership has yielded rich dividends. From 1985 through 2009, ERCs have produced 1,700 invention disclosures, had 621 patents awarded, granted 2,097 patent and software licenses, and spun off 142 firms with 1,452 employees; and the graduated ERCs have been responsible for a substantial majority of these.

The graduated centers have also been responsible for many major products and processes that have been commercialized by industry, including a host of engineering software, new materials development, thin film deposition processes, medical devices, sensors, detection systems, bioprocess therapies, prosthesis, electrical control devices, and many more. A 2009 survey of innovation in current and graduated ERCs estimated that the total market value of these contributions is in the hundreds of billions of dollars. Examples for the graduated centers are the inventions of a NiAl underlayer for magnetic media that made possible small, high capacity hard drives for laptops and MP3 players ($100B market); key developments leading to the MPEG-2 international standard format for digital video (several $100Bs market); biphasic waveforms that made possible portable and improved defibrillators (>$10B market); the multiphase voltage regulator now in every computer with Intel processors (multi-$B market); and the hardware and software that made possible broadband satellite internet broadcasting (approx. $1B annual market).

Another primary driver of the ERC program is the education of engineering and science students who understand and thrive in a cross-disciplinary, team-oriented research environment and are well-equipped to solve the complex technical problems facing us today and in the future. The ERC program embodies a wide diversity of individual disciplines, including mathematics, physical sciences, computer science, health sciences, social sciences and all of the engineering fields, including bioengineering and biomedical engineering. During the life of the program to date, 4,071 bachelors, 3,654 masters and 3,786 doctorate degrees have been granted to ERC students. The centers have also had a significant influence on the curriculum of their institution, integrating research and education and accounting for 133 new degree programs, 20 degree minors programs, 830 new courses, 1,581 modified courses, and 206 textbooks. Eighty percent of employers say that ERC graduates are more effective than their non-ERC peers, giving them high marks for overall preparedness, depth and breadth of technical knowledge, ability to work on interdisciplinary teams, and ability to integrate knowledge to solve problems.

One avenue of assessing the long-term impact of ERCs is to look at the acclaim the centers received since graduation. Many of them have been honored with various awards and recognitions for their post-graduation research and education achievements. In the area of research, these honors include several major professional society awards, recognition in professional journals, industrial recognition, and press coverage. Illustrative of the favorable reputation that many of the graduated centers enjoy are the numerous multi-million dollar federal grants they have received and the fact that two of the centers were key in recruiting a high technology major research center and two automotive assembly plants to their locales. For the latter center, a recent NIST-funded survey reported that it had a $3B economic impact on its state, with the creation of over 1,400 jobs in the past two years. Examples of awards, recognition, and press coverage for post-graduation achievements in education include a county school award recognizing excellence in pre-college teaching modules, graduate student fellowships from university donors, major technical society education medals, best paper awards, and a multimillion dollar, multi-institutional NSF education grant.

Perceptions of NSF’s Role in the Transition Process

NSF’s policy for ERCs is that, by the end of the 10-year (formerly 11-year) cooperative agreement, they are expected to “graduate” from the program and become self-sustaining entities, unless they choose to compete for a brand-new ERC award with a significantly different focus and are successful in that competition. NSF’s stated policies regarding recompetition and self-sufficiency have evolved over the years, and the perceptions of the centers regarding these NSF policies, and the likelihood of their securing a new ERC award, were in the early years of the Program an important factor in how they approached transition planning. Once NSF's policy on this was clarified after the experiences of the first few year classes, few of the centers pursued renewed ERC funding.

Over the years, nine of the graduated centers reported that they chose to apply for a second ERC award; only three of them were successful. Unfortunately, a substantial majority of those who unsuccessfully applied felt there were negative repercussions as a result of not receiving another award. About half of the centers saw a negative impact on the degree of support they received from industry and on their subsequent planning decisions, and over a third of them perceived a negative impact on their reputation in the field.

Most of the graduated centers questioned the 10- to 11-year period of support as being arbitrary[8], and 75% of them thought that NSF's assumptions about self-sufficiency were overly optimistic. They noted that some centers reach maturity early and then decline, while others are still at the state of the art at 10 or 11 years. Many felt that NSF hadn't adequately considered university politics, where external funding is said to be the driver for everything, or that industry expectations often differ from those of NSF. Their perception was that industry considers education programs to be the responsibility of the university, and that although companies value longer-term fundamental research—which for the most part was supported through the NSF funding—most of them are generally unwilling to support it.

One of the graduated centers, which decided to disband, questioned NSF's basic assumption that sustainability after graduation is desirable or necessary, because they see the research world as being completely different from what it was when the Program was first begun. They argued that the first several year classes of centers had already achieved the overall NSF ERC goals of boosting industry in areas key to national competitiveness and changing engineering education, that innovative approaches to engineering education are now standard practice in academia, and that, for many of the centers, the industry in their field was already mature by the time of graduation. Expecting industry to jump in and fund the center, according to them, was a naïve view of the marketplace.

The vast majority of ERCs also felt that circumstances regarding sustainability differ from center to center, with many variables, such as maturity of the field and time to market in their area of technology, affecting the ease of attaining self-sufficiency. Some centers found it difficult to develop viable engineered systems within 10 years in their area; others experienced a maturing of their technologies, making sustainability questionable; and yet others reported that some fields offer more opportunity for external funding than others. One center director felt that the variables of adequate infrastructure funding and commitment of directors and support staffs were critical and affected all graduated ERCs. Techniques employed to counteract some of these variables during transition included expanding the center's research scope, planning for new initiatives and research focus, and leveraging the center's test beds and facilities to provide services to industry and government agencies for a fee. Interestingly, one center director resigned at graduation and

[8] It should be noted that the imposition of a finite life for ERCs was requested by the Office of Management and Budget in 1986 and has since been formalized for ERCs and other major NSF centers at 10 years by the National Science Board.

closed down the ERC. However, its Industrial Advisory Board asked the university to find another center director and resurrect the ERC. It is now a healthy center with strong industrial support.

Although a substantial majority felt that NSF's assumptions about self-sufficiency were flawed, 60% of them reported that a 10-year period is sufficient for a center to become established and to change the culture of engineering education and research in an academic institution. The other 40%, however, expressed reservations or concerns. Several believe that 10 years is insufficient considering political issues in the academic world and the time required to achieve the use of new technology, especially in the biomedical area. They also noted that, in addition to needing a sufficient timeframe, transition success is dependent on several other factors, such as the people involved, changes in center and/or university leadership, continued industrial support, and whether the usually relatively superior work of ERCs is acknowledged internally by the institution. One center director from a more recently graduated center was reluctant to give credit to NSF for injecting a cross-disciplinary culture into the university. He noted that it is now widely accepted that the function of a modern university research center in engineering is to promote and integrate cross-disciplinary research, education, and industrial collaboration, and that is what universities expect of all of their engineering centers, independent of NSF (recognizing, however, that the ERC Program was a major driver of this change in its early years).

Despite concerns about self-sufficiency assumptions and the 10-year time frame, virtually all of the centers reported that the NSF culture involving integration of research, education, and industrial interaction with a focus on cross-disciplinary, engineered systems research was extremely helpful in strengthening and sustaining the center before, during, and after graduation. Most felt that the cross-disciplinary engineered systems approach was key in making their research successful and provided them a competitive edge after graduation Others reported that the ERC culture provided the basis for faculty and students from different departments to learn to work together, become more cognizant of each other's disciplines, and become more in tune with "big picture" issues related to technology development. Some graduated ERCs noted that relationships built with other institutions while they received NSF funding have fostered their current collaborations with these universities. Only one center reported that the NSF ERC culture was no longer helpful after graduation.

Most graduated centers praised NSF's assistance in managing the transition process. Examples of NSF assistance ranged from guidance on alternative funding, business development, and self-sufficiency plans and strategies, to providing pressure for results and survival and growth plans, to helping negotiate with university administration, and in some cases, to providing no-cost extensions and supplemental funding. A few centers did feel, however, that although NSF was very helpful during the life of the ERC, they did not provide much assistance during the transition process. One center even thought that NSF didn't really care about graduated centers and about the consequences of the transition process. (This comment was from one of the earliest centers, which graduated before it became routine for NSF to invite graduated-center directors to come to the ERC Annual Meeting to share their transition experiences in detail with other graduated ERCs and with the currently funded ERCs.)

Some of the graduated centers offered suggestions for NSF to help facilitate the transition process and address the fact that even the most successful ERCs have difficulty retaining their ERC-like characteristics after NSF support. The most vulnerable post-ERC program elements are generally thought to be: basic fundamental research, center infrastructure, undergraduate students, and outreach programs. In most cases, faculty are able to continue to find support for graduate students, albeit often at a reduced level, but support for undergraduate, outreach, and minority student programs is usually more difficult. One recommendation is the development of some type of NSF-industry matching funding program that would reduce the risk of industry in utilizing new technologies developed by the ERCs. Similar programs have been implemented by other federal agencies such as NASA's very successful program to stimulate the use of NASA-developed technologies by industry. Other suggestions include having someone from the NSF staff or previously graduated ERCs provide assistance during the transition process to review progress and assess projections, having the NSF program manager provide more active assistance in this facet of the program, or having the centers maintain their involvement in the program and the imprimatur of NSF through supplemental post-graduation funding for specific education or diversity outreach activities. An advantage of the latter suggestion is that it should increase the likelihood of centers, and their home universities, continuing to think of themselves as part of the ERC family, having the status of the NSF stamp of approval, which likely would have a positive impact on these center's ability to maintain ERC-like characteristics and to maintain and find additional support from other sources, especially federal agencies.

Although not mentioned specifically, the current survey also confirms some of the recommendations from the previous SRI study that continue to be relevant, such as allowing ERCs that continue to be viable centers of excellence to re-compete without being required to reinvent themselves, or permitting an extended period of support as justified by review, either for the entire center or for a portion of its programs—especially the vulnerable areas of funding, such as basic research and infrastructure. Other, low-cost ways to help centers continue to feel part of the ERC family could be occasional NSF participation in their industrial member conferences or in press releases announcing major awards from non-ERC NSF sources, both of which would emphasize the NSF's stamp of approval and continued support.

Was It All Worth It?

The simple answer is "Yes." All 26 graduated centers responding to the survey strongly felt that the effort involved in being an ERC was worth the benefits and results. Benefits reported included early development of leadership, where for some of the centers, several department heads and deans had their start in the ERC; increasing the visibility of the university through collaborations with industry and other institutions; establishing multi-university collaboration that otherwise would have been impossible; and bringing a sea change to the university's attitude regarding multidisciplinary efforts.

In discussing the best and worst aspects of life as an NSF-funded ERC, the graduated ERCs cited the <u>best aspects of life as an NSF ERC</u> as:

- Teaming and visionary projects that are beyond the capabilities of single investigators
- NSF prestige

- Funding to provide flexibility to start projects quickly
- Fostering a cross-disciplinary culture, systems approach, and industry orientation
- Integrating research and education
- Positive impact on individual students, faculty, and university administration
- Opportunities for collaboration with other departments, other institutions, and industry
- Faculty training and the development of the next generation of engineering leadership.

Despite their very positive responses to being an ERC, many of the centers also listed what they considered the worst aspects of life as an NSF ERC as:

- Having to deal with administrative setbacks due to department processes and politics
- Dealing with the burdensome amount of reporting and bureaucratic oversight
- The overall intensity of NSF interaction causing stressed-out faculty and center leadership
- Constantly changing reporting guidelines.

In addition to experiencing the pros and cons of life as an NSF-funded ERC, the graduated centers also have had an opportunity to view life as post-NSF center. They consider the best aspects of having survived the transition process to be the absence of NSF reporting, oversight, and micro-management. They saw the other benefits as being extensions of what had begun when they were an NSF ERC such as:

- Continued vigor among faculty to pursue team and interdisciplinary aspects
- Recognition from industry and continuation of industrial partnerships
- Gratification of seeing their technology making an impact in the marketplace
- Changing culture of the university toward systems-oriented multidisciplinary research
- Continued success and growth as a major university research center.

The absence of NSF funding and prestige created several difficulties for all of the graduated ERCs. They listed the worst aspects of post-NSF life as a center as:

- Having to constantly justify the center internally
- Difficulty in obtaining funds and inability to get long-term continuing support
- Loss of NSF funds and prestige for leveraging other funding opportunities
- Inability to continue to support educational outreach
- Reduction in the number of companies willing to become members of the center
- Absence of NSF attention in observing progress and helping to address difficulties.

In reviewing what the centers felt were the best and worst aspects of being an ERC, both pre- and post-graduation, it is interesting that NSF oversight and guidance are seen as both a burden and a blessing.

Conclusions

Despite the fact that a significant majority of graduated centers felt that NSF's assumptions about self-sufficiency were overly optimistic and despite the difficulties and challenges, most of them seemed to have weathered the loss of NSF funding reasonably well—albeit with reduced funding and with fewer faculty, students, and industrial sponsors in most cases. A substantial majority of the graduated centers continue to be successful as university research and education centers of excellence, with 82% of them continuing to exist as functioning units on campus with external support. Six of the centers have disbanded at some point after graduation; all of these were in the first four year classes where re-competing for a new ERC was a popular, but mostly unsuccessful, transition strategy.

Most of the continuing graduated centers have been successful in maintaining the key characteristics of an ERC and in educating and producing graduates with both broad and deep technical expertise that is prized by both industry and academia. The mission, staffing, and research programs of the centers have adjusted to the changes in funding and in their overall fields of research and industry, with increased focus on short-term problems, but the centers continue to achieve an impressive list of advances in knowledge and technology and products and processes that have been commercialized by industry.

The most vulnerable post-ERC program elements are generally observed to be basic fundamental research, center infrastructure, undergraduate student involvement in research, emphasis on diversity, and education outreach programs. In most cases, faculty are able to continue to find support for graduate students, even if it is reduced, but finding support for undergraduate, outreach, and minority student programs is often more difficult. Because of this and because of the other impacts of the loss of NSF funding, though most of the centers praised NSF's assistance in managing the transition process, many of them felt that additional support during the transition process and some flexibility in both funding and life span of the ERCs should be considered by NSF. Obviously, NSF would need to balance the tradeoff between helping sustain existing mature centers and establishing new ERCs.

APPENDIX I

CASE STUDIES

Case Study
ERC for Computational Field Simulation
Mississippi State University

The NSF ERC for Computational Field Simulation at Mississippi State University (MSU) was initiated in 1990 as a multidisciplinary academic research center conducting a strategically coordinated research program to advance the U.S. capability in the use of computational simulation in engineering analysis and design as well as in scientific research in general, reducing the time and cost of complex field simulations.

The ERC at MSU was cited by the Director of NSF in the January 1999 issue of *ASEE Prism* as a prime example of a successful NSF ERC, noting that this ERC "effectively demonstrates that you can institute change in a very positive way." The Center did bring major change to MSU, most notably by establishing a pattern of cross-disciplinary research. The ERC also established a new multidisciplinary graduate program in Computational Engineering cutting across engineering, computer science, and art. Along with the Department of Art and the School of Architecture, the ERC facilitated new graduate degrees in animation and electronic visualization (MFA in Art) and in electronic design (MS in Architecture).

Graduating from the NSF ERC program in 2001, the Center now continues in an expanded mode as the self-sufficient High Performance Computing Collaboratory (HPC^2), formed in 2003 with funding from a range of federal agencies and industry. The HPC^2 is a confederation of member centers and groups that share: (1) a common core objective of advancing the state of the art in computational science and engineering using high-performance computing; (2) a common approach to research that embraces a multidisciplinary, team-oriented concept; and (3) a commitment to a full partnership between education, research, and service. After the transition from NSF support, the HPC^2 was comprised of five independent centers, broadening the focus to include: computational structural mechanics and materials with applications to advanced vehicular systems; computational physics, chemistry, and biology; and remote sensing through satellite technology with applications that include aquatic and agricultural areas—as well as extending the service mission to support users of the DoD HPC systems.

The transition from an NSF ERC to successful self-sufficiency took place over a two-year period following graduation. The first realization was that, with multiple sources of funding directed at specific research efforts, the NSF ERC model—with its balanced emphasis on research, education, and outreach—could not be sustained. The second realization was that the success of the NSF ERC enabled a significant broadening of the scope of research effort related to HPC, and thus a significant widening of the range of funding sources. The third realization was that the NSF ERC had developed very strong individual leaders who could function best, given this broadening of scope, in a collaborative effort of individual entities.

Center directors initially planned to maintain a single-center type of organization with a much broader scope and a continued common theme of computational science and engineering using HPC, as there was a strong desire within the university to preserve the ERC brand name. But that concept evolved into a confederation of centers focused on cross-disciplinary research in computational science and engineering, using HPC as a more viable operational mode, which allowed the separate centers to operate more efficiently while still maintaining HPC^2's stature as a single entity. There has been significant broadening of the breadth and disciplinary composition of participating faculty commensurate with the expansion of scope of effort since graduation. The common theme of computational science and engineering utilizing HPC that is the legacy of the NSF ERC now encompasses faculty from the College of Engineering and the College of Agriculture, as well as from a wider range within the College of Arts & Sciences. A single HPC^2 director coordinates the overlapping and collaborative activities of the various centers.

At the time of graduation from the ERC Program, the Center's budget was roughly $17M; today, HPC^2's total budget is just under $50M. The total number of people involved in the Center has grown from 245 to 486. The ERC was instrumental in attracting Nissan to build a large plant in Mississippi. The Center's impact since 1990 includes roughly $410M in research expenditures, with a total economic impact of slightly over $3B, providing MSU with a showcase for regional economic development.

Case Study

Advanced Electronic Materials Processing Center
North Carolina State University

The NSF Center for Advanced Electronic Materials Processing (AEMP) was established at North Carolina State University (NCSU) in 1988 and graduated from the ERC Program in 1999. The original mission of the Center was to develop a type of advanced processing techniques for silicon-based microelectronics known as single wafer processing. In 1988 this was a relatively new concept that was actively being pursued by all the major semiconductor companies. Approximately one year later, the SEMATECH Corporation supplemented the NSF ERC funding with a Center of Excellence in the same general area. The SEMATECH funding continued until 1997 and in 1998 a second supplemental research program was started jointly by SRC and SEMATECH, called the FEP Research Center. Industrial participation in the Center was primarily through the semiconductor industries supporting SEMATECH and SRC. The AEMP Center was considered by the faculty involved and by its industrial partners as a very successful center. By the end of the NSF ERC support the Center had graduated over 210 MS and PhD students, with over 180 going into industry, and had over 750 journal publications and 10 issued patents.

In the years immediately following the termination of NSF support, most of the researchers continued research activities within the SRC/SEMATECH FEP Center established in 1998 and funded until 2004. This Center involved seven universities and had as its major research thrust the development of critical semiconductor process technologies for pushing silicon CMOS devices to the ultimate scaling limits, as identified in the National Technology Roadmap for Semiconductors. In particular, the emphasis was on the development of advanced high dielectric constant materials for gate dielectrics and selective epitaxial techniques for source/drain contacts. While these research goals were related to the original NSF Center, they were slightly different as industry had adopted by this time most single wafer processing techniques.

The AEMP Center no longer exists as a named Center at NCSU. There are several reasons for the disbanding of the Center. For one, several of the original key faculty members have retired; in particular, the original director left the Center in 1996 to become dean of the College of Engineering. More importantly, however, has been the evolving research interests of the semiconductor manufacturing industry. The size of silicon CMOS devices is rapidly approaching ultimate limits below which devices can no longer be scaled. Thus, the interests of the semiconductor industry have shifted from silicon-based materials and device research to exploring other materials and device concepts that might be important beyond the ultimate scaling limits for CMOS devices. The semiconductor industry through SRC and SEMATECH no longer funds major academic research centers in the area of the original ERC/SRC center. Researchers tried to obtain major research funding in the emerging areas of molecular devices, but were not successful in transitioning to a major center comparable to the NSF ERC.

The AEMP Center has had a substantial, lasting effect on research at NCSU. The Center was a major factor in getting funding for the Monteith Research Center on the NCSU Centennial Campus. The research laboratories established for the NSF center still provide important research facilities for NCSU researchers. These facilities are now identified as the NCSU Nanofabrication Facility and the Triangle National Lithography Center, which is part of the NSF-funded National Nanotechnology Infrastructure Network. The NSF Center resulted in a number of additional faculty positions which still exist at NCSU. The faculty associated with the original Center are still active in research and have individual research grants from SRC, SEMATECH, NSF, and the semiconductor industry.

Case Study

Optoelectronic Computing Systems Center
University of Colorado

The NSF Optoelectronic Computing Systems Center **(**OCSC) was founded as an ERC in 1987, a member of the third "class" of ERCs. It was an internationally recognized center for research on the use of light to process information at capacities that exceed the capabilities of alternative processing technologies. The application areas for this photonics research were quite diverse. A few of the many OCSC initiatives were automating the search for cancerous cells on x-ray images, replacing wires with light beams inside computers, sensing chemical imbalances in people via the interaction of light with respiratory gases and blood, and achieving such a large depth of focus for cameras that lens focusing would no longer be necessary.

OCSC was a driving force behind making the Rocky Mountain region an internationally known area for photonics by helping to create a unique environment for photonics-related businesses. The Center was very instrumental in establishing the Colorado Photonics Industry Association (CPIA), which fosters relationships among Colorado's many photonics companies. CPIA continues to be a successful organization.

Part of the culture that developed at OCSC during the ERC years was the value and excitement of creating new businesses to exploit emerging technologies. This entrepreneurial focus led to the formation of 14 companies that have used Center-developed technologies. The success of some of these companies increased confidence that the Center would have a significant source of financial support following graduation. A couple of noteworthy examples are (1) the manufacture of digital 3-D systems for cinemas based on the Center's liquid crystal-on-silicon modulator technology, and (2) the manufacture of miniature imaging systems with unprecedented depths of focus based on the Center's patented wavefront coding technology.

Following graduation from the ERC Program in 1998, OCSC was operating for the first few years on about $30,000 per year of royalty funding that went directly to the Center, based on an agreement with NSF to do so with the commitment of the Engineering Dean and University of Colorado administration. This agreement was based on a model set forth in the last few years of proposals to NSF that promised in-perpetuity operation of OCSC founded on a growing royalty stream from intellectual property (IP) generated by the Center. OCSC was successfully using these funds, in accordance with the agreed-upon model, to support fellowships for optics students, highly leveraged equipment matching for collaborative facilities, seed funding for new group grant activities, and matching funds for new optics faculty startup packages, to give just a few examples.

However, when the royalty stream became large enough for the Dean and University administration to notice (well over $1 million in 2005), the Dean decided it was his prerogative to cancel the agreement with NSF. The result was that the royalty funds became the property of the College of Engineering. The loss of this revenue stream had a devastating effect on the finances of OCSC and eventually resulted in the disbanding of the Center.

Case Study

Low Cost Microsystems Packaging Research Center
Georgia Institute of Technology

Established in 1994 as an NSF ERC, the Packaging Research Center (PRC) graduated from the ERC Program in 2006. Founded and directed by Prof. Rao Tummala and funded by NSF, the State of Georgia, and the global electronics industry, the renamed Low Cost Microsystems Package Research Center at the Georgia Institute of Technology (GT) continues to operate as an ERC-like center with an integrated approach to research, education, and industry collaborations, but on a smaller scale than previously.

In research, the PRC began with its pioneering concept of System-on-a-Package (SOP), as an advance over the System-on-a-Chip (SOC) paradigm that was dominant in computer chip packaging at that time (the mid-1990s). Due largely to the work of the PRC, the SOP concept is now widely accepted and validated in industry, since this is the only way to deal with devices that do not scale like CMOS, such as RF, MEMS, sensors, and photonics systems. To stimulate and commercialize the global interest in SOP, the PRC formed a number of industry consortia involving more than 100 cross-discipline faculty and students focused on a variety of leading-edge topics and involving some of the most advanced semiconductor, package, and system companies. The PRC maintains six core research areas, each headed by a faculty. During its 15 years, the PRC has generated in excess of $228M in research funding for its pioneering SOP research, which has resulted in 1,129 publications and 185 inventions to date. The total quantifiable contribution of the PRC to the Georgia economy over its life as an ERC was estimated at $351 million; although not quantified, that contribution has continued to grow since graduation.

In education, the PRC continues to lead the global academic community by offering seven undergraduate and 11 graduate-level cross-disciplinary classroom courses and two hands-on courses. It has produced two textbooks, one undergraduate and one graduate level, each the first one in their topic area. Additionally, two reference books have been published. In total 181 undergraduate, 283 masters, and 198 PhD degrees, all specializing in packaging research, have been conveyed through the PRC program.

In the area of industry collaborations, the PRC pioneered what it calls a "US-Fraünhofer culture," which is a mix of a US-style culture for innovation and a Fraünhofer-style culture for technology transfer. The PRC has been experimenting with and refining this model since the last phase of ERC funding. This new model has resulted in a growth of industry memberships from approximately 15 companies at the end of NSF funding to some 65 companies today. To achieve this growth, the Center developed a team approach that involved students, with academic faculty as their advisors, and research faculty with industry engineers as their mentors, in every research project. The PRC views this type of industrial collaboration as a critical element of its long-term sustainability. This strong partnership with industry has resulted in more than 357 internships, 323 PRC graduates employed by industry, 235 distinguished industry lectures on campus, 97 industry thesis committee participants, and the granting of 33 licenses, 4 spin-off and 4 spin-in companies into the Atlanta area, and over 64 engineers assigned to campus.

In summary, the PRC, as a direct result of NSF ERC and Georgia Tech, became and continues to be a global leader in leading-edge packaging research, education of globally competitive engineers, and a broad-based industry collaborator. To achieve this, it has attracted a number of faculty leaders who began to spin off their own programs into satellite centers, thus making GT even more comprehensive than before. While the PRC continues to explore new frontiers toward nanoscale, the SOP technology that it developed is being deployed worldwide. Major companies such as IBM, Intel, TI, SONY, Medtronic, Motorola, Matsushita, Nokia, Infineon, ST Micro, and Samsung, among 100 others, have accepted and are adopting key elements of SOP. The societal impacts of PRC's SOP are far reaching in two ways: the SOC is no longer viewed as strategic and SOP is the only alternative to SOC. Unlike SOC, SOP leads to both convergent and heterogeneous systems with the highest functionality, lowest cost in the smallest size to serve not only traditional computing and consumer systems but also biomedical and energy systems.

Case Study

Particle Engineering Research Center (PERC)
University of Florida

The Particle Engineering Research Center (PERC) was established at the University of Florida (UF) in 1994 as the "NSF Engineering Research Center (ERC) for Particle Science and Technology." The mandate for the Center was to conduct industry-relevant research in the area of particle science and technology. From its inception, PERC has served as a unique catalyst for synergistic interdisciplinary collaborations that have led to over $50M invested in cutting-edge research, the education of more than 800 students, fruitful collaborations with over 100 companies, and the successful transfer of more than 10 major new particle-based technologies. In 1997, the Center moved into the newly-constructed Particle Science and Technology Building funded by the State of Florida as a testament to its commitment to this enterprise. PERC was one of the very few NSF ERCs for which the host university built a separate building completely dedicated to the Center. In 2001, the Center was renamed the Particle Engineering Research Center (PERC) and the Characterization Research Instrumentation and Testbed (CRIT) facility became the PERC R&D Facility and was made a UF auxiliary in the summer of 2004. With the impending successful completion of the NSF 10-year funding cycle, the PERC "Service Center" began charging fees for usage of equipment and technical staff time to help offset costs. This was part of the Center's self-sufficiency plan for post-NSF operations.

Also part of the self-sufficiency plan was the strategic evolution of the Center's original research scope to better address societal and industrial needs. In the early years, the Center focused on four thrust areas: (1) online analytical systems; (2) concentrated particulate dispersions; (3) transport and handling; and (4) treatment of particulate effluents. A major shift in the research focus took place in 2000 with a new research thrust in Nano-Bio Systems. This change in direction was sparked by increasing national and international interest in nano- and bio-technologies and the realization that particle-based nanotechnologies would play a significant role in these emerging fields. In 2007, PERC team members, in collaboration with other faculty researchers, were awarded a State of Florida Center of Excellence grant, the "Center for Nano-Bio Sensors," for translational technology developments focused on sensors for healthcare and homeland security applications. In 2008, PERC researchers joined hands with their counterparts at Columbia University and were successful in establishing a joint NSF I/UCRC (Industry/University Cooperative Research Center), the "Center for Particulate and Surfactant Systems." These evolutions have proven to be instrumental in the long-term survival of the Center.

Five years after successfully graduating from the NSF ERC program, while PERC continues on its path of success, the loss of NSF funding has been felt. Current annual funding totals approximately $2M, which is about one-third of the Center's ERC-era funding. PERC now relies upon federal, state, and industry grants, its industry partners, and the Service Center to generate the research and operational funds necessary to maintain a healthy research program. In June 2008 the Center held a two-day retreat to address this issue, reevaluate itself, and develop a new vision and strategic plan to propel PERC into the future. PERC's next-generation vision is to *"Innovate and transform particle science and technology advances into useful applications for sustained societal well-being."*

PERC aspires to maintain its leadership in the broad field of particle science and technology by enhancing the Center's activities in translational research and technology transfer to carry out its mission—"to better serve society through education, innovation, and advancement of particle science and technology."