Final Report

Center for Collaborative Manufacturing

Purdue University

December, 1999

This report attempts the daunting task of summarizing fifteen years of work covering a wide range of activities by more than 1200 people. To simplify our task, we might justifiably confine the report to the final five years, the period after the ERC received a "restart" grant to operate under the new designation of Center for Collaborative Manufacturing. However, that isolation would fail to illuminate the critical earlier development--the ten years when the ERC operated as the Engineering Research Center for Intelligent Manufacturing Systems. We have always argued that the big picture perspective--the so-called "system view"--was the proper way to understand what an ERC is all about, and therefore take this broader approach here. More detailed data are, of course, available in the form of annual reports and indicator reports.

I. Historical Overview.

It may be difficult to reconstruct the mood affecting the nation in the early 1980's, when the ERC program was conceived, but those origins were critical to the structural design and mission of the Purdue ERC.

Ronald Reagan was in his first term as President. The Berlin wall still stood, though the Cold War which had dominated national security concerns seemed to be thawing. Concern had shifted to economic security, which seemed threatened by massive trade imbalance, a formidable block of Pacific-rim competitors, and the prospect of a unified European economic community. Japan and Germany in particular--the defeated enemies of World War II--seemed to be emerging as the dominant economic adversaries. Whole market sectors (such as consumer electronics, cameras, power tools, motorcycles, and machine tools) were being taken over by foreign competitors. Although some were still in denial, many people were deeply concerned that America's future--particularly its economic power--was in peril.

The demonstrations of foreign superiority in speed, cost, and quality provoked alarm, but no clear response. After decades of complacent satisfaction with the status quo (American companies were already the world leaders in manufacturing; why change anything?), the ability to innovate in manufacturing industries was weak. An entire generation of managers and workers had succeeded by shunning change; in fact, the keys to success were explicitly understood to be the elimination of variations and prevention of disturbances.

Meanwhile, American universities were neglecting research into manufacturing and most other commercially relevant issues. In a few institutions, strong individuals managed to keep academic research in manufacturing alive. Examples are H. Voelker, K.K. Wang, G. Boothroyd, M. Barash, and S. Woo (all of whom were educated in other countries). But most American research universities regarded the subject as uninteresting or worse. Few American-educated students considered manufacturing to be respectable enough to enter into their career plans.

That was the social and political environment in which the National Academy of Engineering conducted its study that led to the formation of ERCs. The study committee,

after analyzing the competitiveness problems and recognizing that the gap between industry and academe was an impediment to long-term progress, concluded that significant restructuring of engineering education and the research culture of universities was warranted. Their recommendation to create the ERC program and the basic outline of its design were intended to effect those changes. The ERC concept was not merely a new way to fund research in a few selected universities. It was a bold plan conceived with the hope that a targeted investment could transform engineering education and, by that means, preserve the long term economic security of the nation.

Fifteen years later, it is difficult to recall how isolated university research was from the industrial needs of the time and to recreate the concern for the future that many Americans felt at that time. The threats of the Pacific rim and a unified Europe and the fear that we had a decade ago now seem exaggerated. With unprecedented domestic prosperity, our confidence in the future is again strong. All of the ERC's company partners now say that their principal challenge is to make enough product to meet demands.

While no one would claim that the Purdue ERC or even the entire ERC program was the primary driving force, it would also be wrong to dismiss their contributions. A general awakening of American consciousness of the importance of reforming manufacturing practices to compete with foreign suppliers was inevitable. *What* to do was not so clear. The Purdue ERC, along with many others of course, helped to guide threatened companies along a course of innovation. We should remember that many companies failed entirely or survived only as much smaller organizations during this period. Those that managed to come through the transition stronger did so in part by adopting the principles advocated by ERCs and similar organizations.

Viewed at the scale of the industry it was intended to serve, the entire ERC program represents a very small investment. No one could have expected massive or immediate impacts. The idea was more subtle than that. By emphasizing university reforms, rather than direct influences on industries, the National Academy committee hoped to create a powerfully leveraged long-term transformation that would continue to feed innovators into the industries for decades to come. While many important research products came out of the ERC, we believe that the most significant contribution is the lasting legacy provided by a generation of students who are better prepared than they otherwise would have been to deal with the competitiveness problems of the future.

II. Impacts of Research.

When we are asked to list accomplishments in research, we can point to numerous contributions that were published in the open technical literature. Over 2400 articles can be credited to Purdue ERC teams. More significantly, however, we can also point to many innovations that went directly into manufacturing companies. The speed of conversion from laboratory to practice can be attributed to three factors that are inherent in the ERC design: (1) the cross-disciplinary teams had both the incentives and the means to solve real problems, (2) the research had interested recipients waiting because it was planned and conducted with the participation of companies, and (3) in many cases the students who

carried out the work went to work for the companies. These factors are not unique to ERCs, but they are not easily matched by single investigators.

Examples of technological advances include a Quick Turnaround Cell for rapid production of one-of-a-kind machined parts, a high-level computer modeling system to support product design and analysis, process models for improved control of several types of unit manufacturing processes, and a very responsive and flexible material handling system with sophisticated traffic control. Along with technological advances, the ERC research provided new approaches to product design, to manufacturing process control, and to system integration.

To expect "block-buster" discoveries or inventions would be to seriously miss the point. That would be like expecting to win the lottery by investing in a mutual fund. Evaluating a list of accomplishments one-by-one would also miss the point, because the ERC is more than a portfolio of research projects. The research program should be taken as a piece of a larger program that includes the education, outreach, and industrial participation elements as mission-critical functions.

Sometimes site visitors, study committees, or other outside observers have misunderstood the ERC to be, in essence, a large research block grant. They focused almost exclusively on our research plans and accomplishments, taking the educational, outreach, and industrial partnerships as peripheral to the main goal. Our view, in agreement with the original intent of the National Academy committee, was that the principal mission was the transformation of engineering education to produce a new generation of graduates that would be better suited to the rapidly changing global competitive marketplace. The fulfillment of that mission required, among other things, conducting the research program in accordance with a long-range strategic plan that was worked out and continually updated with the assistance of industry. That approach guaranteed both relevance and a "systems" perspective to guard against parochial interests of individual researchers.

All of the work was conducted with multidisciplinary teams, consisting of multiple faculty (from more than one department), graduate students, undergraduates, representatives of industry, and sometimes even faculty and students from other universities. The *experience* of conducting industry-relevant research in this way was as important as the research products, because the mission was to change the *system* of innovation, not merely to create some particular innovations. If, for example, the primary goal had been to solve some identified problem in the most expeditious way, we would have hired full-time experienced research staff. The Purdue ERC had none of these. We strongly believe that engaging in research helps students to become self-sufficient learners--a quality that is more vital to their career success than it has ever been.

The theme for the Purdue ERC has always been Manufacturing, in the "big M," or broadest sense. We labeled the focus as, first, Intelligent Manufacturing Systems and later as Collaborative Manufacturing. Those terms were really just descriptions of trends we believed (and history eventually vindicated) were important to the broad subject of Manufacturing. In fact, the term Manufacturing itself was sometimes interpreted by others more

narrowly than we intended. We always gave it the broadest interpretation--all of the issues involved with creating products. Our core reason for wanting the broad interpretation was and still is our belief that students need to understand more than one aspect of the process in order to perform effectively within a particular job function. If the focus of the center were to be just design, or just logistics, or just machining processes, then the subject matter could be (indeed, is) handled within a single discipline. Thus the broad view is linked directly to our role as a multi-disciplinary center that spans the traditional disciplines.

The Purdue ERC successfully anticipated critical research issues years ahead of other research groups. We could not be certain in advance that we had chosen correctly, but the passage of time verified that we had. The ability to anticipate correctly was a direct consequence of the system-oriented strategic planning that is characteristic of an ERC. It is very unlikely that, without the discipline for planning and the inclusion of industry, the individual researchers would have reached those conclusions on their own. Single investigators or narrowly focused small groups simply do not approach research in that way. Just as importantly, the strategic planning helped the ERC to avoid pursuing many issues that were "hot" at the time and later faded. Robotics and machine vision are examples of topics that we abandoned after our industry partners warned us that they had already satisfied their interests in those areas.

One unfortunate consequence of being "ahead of the pack" is that the ERC may never receive the leadership credit it deserves, because the words used to describe the themes changed after we identified them in our own terms. The focus that we labeled Intelligent Manufacturing Systems later came to be known as Agile Manufacturing, Rapid Response Manufacturing, Time-Based Competition, and Reconfigurable Manufacturing. Over the same period, our phrase (IMS) came to be associated with a controversial international research program initiated by the Japanese. The themes we identified in 1994, when we changed our emphasis to Collaborative Manufacturing, subsequently emerged under different names, such as e-commerce, supply chain integration, and web-enabled manufacturing.

The most important consequence of foresight was that the students were well prepared for the most serious concerns of the times when they graduated. They were already familiar with the emerging issues.

III. Impacts on the University.

The ERC has had a profound effect upon the research culture at Purdue. Previously, most of the research was initiated by one professor, or at most a few professors of the same department, and they worked closely with only their own graduate students. There was little possibility of cross-disciplinary research in an area like manufacturing because there was no mechanism for even identifying the research problems, let alone solving them. There were so many obstacles that faculty were reluctant to engage even if they possessed a strong inclination for cross-disciplinary work. Now there is an organized mechanism for cross-disciplinary research with enough of a critical mass to make a difference. The bene-

fits are obvious to faculty, administrators, and students. For the first time, there is meaningful technical interaction among students of different departments.

Organizationally, the ERC functioned as an integrating mechanism across the disciplines. It was never expected to become a new department or to offer its own degrees. Some universities--mostly smaller ones--have established Manufacturing Engineering as a new discipline, but we continue to believe that both students and employers are best served by deep knowledge within one of the traditional disciplines combined with experience in team-based problem solving. Contemporary work in Manufacturing often requires that combination. Straddling the technical disciplines and the permanent organizational structures of the university, without seeking to become one of them, demands agility. Any ERC needs the enthusiastic cooperation of the departments, and therefore cannot compete with them or draw resources from them. Thanks to careful management, each of the faculties saw the ERC as an asset that contributed to their own objectives and achieved something worthwhile that they could not achieve on their own.

The benefits of working with industry emerged rather quickly. The halo effect generated by the initial award brought us equipment contributions that we otherwise would not have been offered. These enabled us to conduct full-scale experiments that might not have been attempted, or at best could have been conducted on much smaller scale. The direct access to industry data and facilities presented other research and education opportunities that could not have been matched in any other way.

These lessons were not limited to those who participated directly in the ERC. Faculty and administrators all over the university took note of the ERC success and emulated what they could in their own initiatives. Several new centers were started, most of them modeled after the structure and policies established by the ERC. We believe, judging from the number of visitors and phone calls for advice, that many other universities have followed suit. We have no way of assessing how far this influence has traveled, but are certain that the Purdue ERC has had a substantial impact as an example.

Another way in which the ERC influenced Purdue is in faculty hiring. Obviously, the increased level of activity created new openings, but more importantly, there were changes in the characteristics of the new faculty sought. Departments, wanting to take advantage of the opportunities, sought people who could be expected to function well in cross-disciplinary teams. Once it became apparent that this kind of work would more likely to be rewarded by tenure and promotion (rather than less likely, as many had assumed) there was a rush to get involved. At that point, the ERC was selecting from among applicants instead of promoting involvement by the faculty.

An observer might argue that some of these changes might have happened even without the influence of the ERC, but no one could dispute the impulse effect and the incentives to do it early. The planned aggressive action certainly accomplished more and sooner than natural evolution would. One further activity that definitely could not have happened without the influence of the ERC was the creation of a Masters' level manufacturing option across all of the engineering schools.

IV. Impacts on Industry.

The basic nature of the relationship between the university and industry has been altered by the ERC. In the early days, we encountered understandable hesitation on the part of companies to invest in university research. They had experienced decades of what they saw as "aloof" or "ivory-tower" academic research that had little to do with their needs. The dramatic public impact of the ERC announcement helped to overcome that initial hesitation for a number of progressive companies. In addition to leveraging the funding from the National Science Foundation, the facilities, expertise, and guidance provided by industry enabled the ERC to attack large scale realistic problems that could not otherwise be addressed in a university. The success of that approach then helped to overcome the skepticism of other companies.

Some sixty-five companies participated directly with the Purdue ERC. The fact that most of these companies stayed with the ERC, some for as long as the entire fifteen years, gives *prima fascia* evidence that they value the work performed.

We have found that the long term relationships go through an interesting learning cycle that seems to be much the same for each company. At the beginning, the discussions involve formal terms of agreement, such as intellectual property rights and reporting mechanisms. The company concerns center around controlling the work to ensure that specific milestones are met, so that tangible returns can be measured in order to justify their financial contributions. In other words, they are thinking of the ERC as a supplier or a contract R & D organization. As they become more familiar with the activities of ERC and realize that the whole is much more than a collection of projects, they begin to broaden their view. For example, they realize that the discussions held with other companies in the room and the opportunities to influence educational reforms have as much or more value than specific project results. Eventually (if the same people are involved long enough), they cease to show any concern for formalities or contract terms because they fully understand and buy into the ERC mission. At that point, the company representatives are "insiders" with just as much devotion to the cause as any Purdue faculty member or student.

Understanding this process of evolution in the relationship helps to reduce conflicts and frustration. In the early stages, we know that we have to focus narrowly on specific outcomes. The ERC needs to help its collaborators provide the kind of justification for involvement that they need.

Examples of these kinds of tangible deliverables include:

- Cummins Engine Company has worked closely with Purdue for some time on advanced process development for hole making technology, employed in their fuel system division for fuel injector nozzles. They now have a patent application in process, based upon the fundamental knowledge generated at Purdue and translated into process application at Cummins. The projected capital equipment savings is more than $4 million by 2005.

- Boeing Commercial Airplane Company makes extensive use of an internally developed machining prediction model. The analysis provides process parameters and is also used for adaptive control of machines. Purdue work on a spindle stiffness model provided improvements to the Boeing software. The impact of the improvements is not yet known, but the software is known to have very high value to Boeing.
- SETCO, a manufacturer of machine tool spindles, benefited from ERC work through improving its spindle design by more accurately predicting thermal distortion of key components. The work derived from a thermomechanical model developed and tested in the ERC laboratories.
- A small, high technology company called Advanced Refractory Technologies is developing a material/process combination that provides superior performance as a coating for Electo-Discharge Machine tooling. The Purdue work supplied the missing knowledge that enabled the process to work with the new material.

As soon as companies realize some of these tangible benefits, they almost always want to hire the students who were involved in the work. Those hires predictably lead to a greater appetite for more recruits, including students working in projects unrelated to those the company was originally interested in. Gradually, the company comes to value the ERC's unique cross-disciplinary educational experience and the industry focused research program, as much for its effect upon the students and the company's employees as for the specific tangible deliverables. In a few cases, companies have acknowledged that the Purdue ERC had a significant impact on their strategic thinking about the future.

The ERC is an engine in a progressive movement that is at least national and perhaps even global in scope. It is not easy for a company that is under short term economic pressures to see that their destiny is entwined with those large-scale long term issues or that they have any ability to influence them. But as the ERC grows its champions within industry--changing the way that they think about universities, research, innovation, and their role in the movement--the strength of the movement grows. This, we believe, is the most profound impact of the ERC.

V. Impacts on students.

From the earliest stages of planning, before even the first proposal was submitted, the Purdue ERC was designed to emphasize the students. More than half of the money received from the NSF over the entire fifteen years went to supporting students. Moreover, we sought leverage from other sources, such as fellowships and gifts, to extend the ERC experience to as many students as possible.

Over its nearly fifteen years of NSF support, the Purdue ERC directly employed over 1100 students, who received the benefits of a special educational experience involving cross-disciplinary teamwork with over seventy companies. These graduates were and continue to be eagerly sought by recruiters. Independent assessments[1], as well as the reports of their employers, testify to their superior abilities on the job. Some of the earlier

1. See the study by the Stanford Research Institute, available through their website at: www.sri.com/policy/stp/erc/

graduates have already risen to high positions carrying broad responsibility. A few started their own companies which have since flourished.

Over 180 Ph.D.'s were completed under the auspices of the ERC, and these graduates have gone on to influential positions throughout the country and abroad, carrying the multi-disciplinary system oriented team values of the ERC culture. From the beginning of the first ERC, we had the explicit objective of increasing the population of faculty at U.S. universities who are oriented toward the needs we perceive. Many of our doctoral level graduates have indeed spread to universities throughout the U.S. and the world and are creating their own programs emulating our own. This "seeding" influence, along with the dispersal of graduates throughout industry, guarantees the continued influence of the ERC values and culture.

Seventy-five different faculty members have been involved at various times in the ERC research teams, including about a dozen from outside Purdue. Some sixty courses were created or significantly modified. Through changes in the basic curricula of the engineering disciplines, the ERC influenced the education of nearly a thousand engineering students per year. In 1997, the Society of Manufacturing Engineers awarded Purdue its prestigious Lead Award in recognition of its outstanding educational program in integrated manufacturing.

The ERC pioneered innovations in such areas as undergraduate participation in research projects, short and medium term graduate internships in industry, and experience in cross-disciplinary team projects. A new kind of financial support for highly qualified beginning graduate students provided several supervised educational experiences in industry. There was a program to involve high school and middle school teachers in Center activities, designed to influence the awareness of opportunities in manufacturing among pre-college students. We also increased our own flexibility to undertake short term projects of only a few weeks or months duration. These might focus on, for example, benchmarking studies, the installation of a new technology, or assessments of alternative approaches to a manufacturing problem. While such short term projects are not normally undertaken in universities, they can benefit students' education and can form a healthy part of an overall program. We developed innovative approaches to the management of such projects to make them compatible with the constraints of an academic environment.

We were delighted with the success of our Summer Undergraduate Research Intern program which employed undergraduate students full time in the summer as temporary members of our research teams. Each summer since we started the program in 1986, we employed as many as 100 undergraduate students per year. Through the REU (Research Experiences for Undergraduates) mechanism, we brought students enrolled in other universities to our summer program for exactly the same experience. We found these students from outside Purdue to be effective contributors to the overall research effort, despite their short time at our campus.

The undergraduate curricula in Industrial Engineering and Mechanical Engineering were revised considerably over the last few years to incorporate modern concepts in man-

ufacturing. It is also far more common than it used to be for undergraduates to elect courses outside their own discipline.

One innovation in graduate education involves a new form of support for incoming graduate students. Students who were selected as "ERC Interns" were guaranteed support by the Center before they identified a major professor and a research topic. Students fulfilled certain responsibilities to the Center until they identified their topic, at which time they continued in the normal Research Assistantship relationship with a particular professor in his or her home school. The student therefore had an opportunity during the first year to explore a range of possibilities before committing to a specialization. The work involved, whenever possible, direct collaboration with industry in short term projects under faculty supervision. The students who had this opportunity were uniformly enthusiastic about their special advantages.

The ERC has for the last several years conducted outreach activities to reach the pre-college population. Our past experience in attempting to recruit women and under-represented minorities revealed clearly that we have to start very early. By the time they are in high school, many qualified students have already formed unflattering images of engineering in general and manufacturing in particular. Others have lost the option of pursuing careers in science or engineering by their choice of courses. For the last three summers we hired two or three middle school and high school teachers to help us with this program. All of the involved teachers incorporated the teaching materials developed in the first summer into their schools. We also ran a teacher institute to spread the materials further.

VI. The future.

It is gratifying to look back upon the accomplishments and to realize how far we have come. Still, in our opinion, the job is far from finished. Despite the general exuberance reflected in the current economy, we believe strongly that core problems in American production industries remain. They are currently disguised by a very strong domestic economy and temporary weakness in the Asian and European economies. But that relative position is not secured by any technical or organizational difference. The foreign competitors will challenge again as soon as their financial circumstances permit--probably within three or four years.

In fact, we believe that there is a greater vulnerability now than in 1985 because many companies are so lean that there is no reserve for further cutting. The comparatively easy "business remedies", such as cost-cutting by downsizing, outsourcing, and shedding of non-essential functions, did not address fundamental weaknesses in the engineering systems. Furthermore, the means by which they will be able to sustain long term innovation is in question. We even see some companies reverting to the old "if it ain't broke, don't fix it" attitudes that impede essential innovations. Many of our industrial partners express great concern for the long term, even as they concede the necessity of focusing on immediate needs. They do not share the complacency often reflected in the public media that the American economy is secure.

For these reasons, the Purdue ERC team will continue to operate, doing all we can to advance the entire set of goals of the original ERC program. At least for the near term future, we will continue to advance the theme of Collaborative Manufacturing and retain the same name.

For the past year, we have been concerned about the scale of support that we would be able to generate from industry after the NSF funding was gone. We have been open with our industrial partners about the changing circumstances. Although their verbal support was strong, we knew that the real test would occur when the time for sending a check arrived. The payment schedule varied by company, so there was no single date for determining the outcome. Indeed, some of the companies have not yet faced that critical moment. However, we are pleased to report that, so far, all of the member companies whose payments have come due have re-enlisted. It appears at the time of this report that the ERC will be able to carry out its plans without sacrificing any of its core functions for lack of funding.

For marketing purposes, and specifically to extend the potential set of sponsors to a larger group of companies, we have decided to divide the research activities into two subgroups. One, which is most closely associated with the activities of the first ten years, will emphasize the "hardware" or "unit process" side of manufacturing. Most of our current sponsor companies relate closely to that work, and our past accomplishments in that area give it a secure, predictable future. However, the nature of the processes we have studied--metalcutting, heat treatment, grinding, and similar heavy industry processes--are of interest to only certain kinds of companies. For that reason, we are going to market our "software" and "collaboration" activities, which are more closely associated with the recent past and are less securely established, in a different thrust. We hope to be able to enlist electronics, pharmaceutical, and perhaps chemical companies in this venture.

At this point, survival of the Purdue ERC is not in doubt. Questions do remain, however, about our ability to maintain all of the elements of our program without the funding and "sponsor's interest" from the National Science Foundation. For example, we are not sure that companies will have sufficient interest in some of our educational and outreach activities to underwrite them, when it means they pay the cost without capturing direct returns. We are expecting some pressure to devote all of our resources to research projects, but plan to defend our overall program as best we can.

VII. Lessons learned.

Carrying out the ERC mission is a continuous learning experience at many levels. Of course, one could say the same thing about life in general, but there are some lessons that are uniquely offered by an ERC because of its special nature. We focus here on a few points of critical distilled wisdom that might help others to enjoy our success and avoid some surprises.

A. Changing culture is possible, but slow and very difficult.

We were eventually very satisfied with our success in changing the culture of the university. However, these changes did not come as easily or as quickly as we expected. Of course, we knew that culture is notoriously difficult to change, but we naively thought that the massive impact of an ERC would overcome any resistance. We overestimated our power in the earlier years, and certainly might have failed to effect the changes we wanted if any one of several key features had been absent. Here are some of the critical elements:

(1) We had firm policies requiring cross-disciplinary teamwork. We would not provide funding to individuals who wanted to work alone, no matter how good their ideas. For the first few years, many professors challenged this policy, either overtly or covertly. Faculty prefer independence, for reasons that are perfectly understandable. But individuals, even very creative and hardworking ones, cannot tackle large-scale, broad-scope problems. It was only by announcing at the beginning a firm policy and then resisting every attempt to subvert it that we were able to avoid a natural drift toward independent work.

(2) We announced and carried out a planned turnover of projects, based upon a system of external reviews. There is a natural inclination for those who are involved early to feel that they are entitled to continuing support. Some relax into a comfortable, low level of productivity. Others may try to divert their attention to something of personal interest, rather than fulfill their proposed plans. For these and other reasons, it was important particularly in the first formative years, to weed out the weakest performers. The "tough reviewing" was also critical to establishing the stature of involvement with the ERC.

(3) We actively sought the involvement of younger faculty. Recruiting and mentoring had to be done carefully, so that ERC support would not be or appear to be an easier path for young faculty. Despite the obvious support of the administration, many junior faculty were advised by more senior faculty to avoid involvement because it was too risky. Initial skepticism took several years to overcome; however, the benefits were eventually apparent to all. We now have senior faculty who worked in the ERC from the time they started as professors, and their commitment obviously protects the ERC values.

(4) The strong, visible support of the Dean of Engineering was essential. The ERC had its detractors within Purdue. Some professors who were denied in their proposals or who were terminated after poor performance awaited opportunities for revenge. Many people were envious of the power or attention or funding. Some department heads, while not hostile to the ERC, had alternative plans of their own which they preferred their own faculty to focus upon. As a new activity without an established home in the organizational chart of the university, the ERC had to fight for its place as a permanent part of the structure. Even with all of the forces aligned, establishing its niche took longer than most of us expected--five to six years. During this time, the Dean had to speak up often in support of the ERC. Even then, we were not really sure the changes would last until a change of Deans without any bad consequences provided the final proof.

Overall, the primary lesson for changing a well-rooted culture is a cliche: it takes patience and determination. For ERCs, the particular lessons are not to underestimate the effort and to establish firm policies early.

B. There is a lot of overhead to running an ERC.

Shortly after the celebration of winning an ERC award, the burdens begin. In addition to all of the launching work, which any outsider could understand and appreciate, the ERC management will be inundated with unexpected workload. Normal days are disturbed by visitors, reporters, people who want to take surveys, people who want information to list in directories or databases, people who want to sell something, people who want jobs, people who want you to endorse something, and various cranks and crackpots. The university, city, state, chamber of commerce, and various others want to showcase the ERC as a civic monument. Some people walk in off the street thinking that, as a federally supported program, the ERC is chartered with the responsibility to help them. These peripheral activities consume large chunks of time and threaten the real mission of the ERC. To some extent, procedures can be instituted to insulate the workers from these distractions, but the ERC management will have to deal directly with many of them. For example, if a delegation of foreign scientists requests time with the Director, there is no one else who can substitute.

Each industrial company sponsor expects individual treatment. As explained earlier, the company relationships are really relationships among individuals, which must be tended with sensitivity to the case-specific circumstances. Each new person, even from companies that have been members for a long time, takes time and attention to bring into the fold. Shortcuts and attempts to leverage, such as large call-out meetings or orientation sessions, never seemed to be fully effective. Even after fifteen years, we have found no substitute for time consuming face-to-face discussions.

Site visits and NSF reporting requirements consume a lot of time--more, we think, than the program managers realize. Taken one-by-one, each of the accountability requirements is quite reasonable, but taken in total and along with all of the other activities that take time away from "doing the job," the reporting burden is a load factor that affects the rate of accomplishments. As one of the few parties that can evaluate the overall effects of its actions, the National Science Foundation should be careful about the balance between responsible oversight and excessive scrutiny. For example, using the ERCs as convenient testbeds for federal accountability experiments or giving encouragement to independent academic studies of ERCs should be undertaken only after determining the costs to the ERCs for responding. All such requirements do add to an already heavy burden and do exact a penalty in other areas.

The lesson for the Principle Investigators of a new ERC is to expect such workloads as part of the obligations they take on. If they fail to plan for the burden or expect their time and money can be devoted almost entirely to conducting the research and education programs, they will be frustrated at best and may fail to satisfy their sponsors at worst. Records should be kept with the expectation that someone may someday ask a question that was not anticipated when the record keeping system was set up. Staff will be needed just to take care of records and reports. Students can be used effectively to conduct tours and to help take some of the "explaining" burden, but the faculty and staff cannot escape similar work.

C. Things change.

Another cliche that has deeper implications for developing ERCs is the fact that nothing remains constant. Despite the care taken in long-range strategic planning, events will overtake any plans. We found that, even with annual reviews and adjustments, we had to completely rethink the strategic plan every three years or so. Personnel change, sometimes when you least expect. We learned early that a tragic death can drastically alter the ERC's ability to carry out its plans in some arena. New faculty or previously undiscovered opportunities can open up new options. A new member company can alter the perspective.

We have already referred to the challenges of maintaining company relationships in the face of continual turnover in their representation. The learning curve seems to require two to three years, but is quite predictable in its course. Of course, it can be interrupted if the company representative is reassigned. In such cases, we find that the process starts over from the beginning with the new person. In other words, it is individuals who learn, not companies. The Stanford Research Institute's finding that "companies" came to appreciate the intangible outcomes of the ERCs should be interpreted only in this limited way. For those ERCs that are still in the formative stage, the lessons are: (1) try to arrange your relationships with companies in such a way that continuity of individuals is maintained as much as possible (e.g., resist any suggestion that a new person rotate through every year), and (2) do not expect the start-up issues to go away after the first few years.

The goals and criteria espoused by the National Science Foundation did not remain static. In fact, in the early years when everyone was exploring possibilities, it seemed that every site visit brought new criteria into play. Of course, success is elusive when the criteria keep changing, so many of us were frustrated until we finally came to accept that change was just part of the environment. In fact, we have argued that companies should learn to embrace change; no less should be expected of ERCs.

Over the last fifteen years, since the formation of the Purdue ERC, the industrial climate has changed substantially. When we began in the mid 1980's, many companies were concerned about the competitiveness of American industry. Their concern translated to enthusiastic support of the ERC concept and high expectations for research results that would be directly useful to them. Later, as many companies were forced by economic circumstances to trim their own headcount, it became much more difficult to enlist new members--they could not justify outside expenditures when their own employees were being laid off, no matter how interested they were. Furthermore, the fact that many of them were not hiring for several years reduced their motivation to work with universities. Over the last few years, the strength of the U.S. economy, coupled with the stagnation of Japanese and European economies, has reduced the sense of crisis. "Competitiveness" is no longer a rallying cry, and in some circles has even become equated (negatively) to layoffs. Formerly large manufacturing companies have trimmed away all but the most immediate and essential functions, often to the extent of severely cutting their R&D capacity. Although the words have changed, the emotional fervor has diminished, and the spotlight of public attention has shifted, the overall ERC goals are still current and critical to national interests.

Conclusion.

Now that we are leaving the program and can speak without being accused of fostering our own interests, we would like to express the conviction that the ERC program is a proven success and should be significantly expanded. The justification is not as a reward for performance, or political pressure, or receiving a just share, but because the program is successfully fulfilling a vital national need that no other program addresses. The early investments, which were prudently limited to experimental levels, were clearly insufficient to fulfill the important national goals laid out in the National Academy report. The intervening years have seen the formation of many center and center-like research programs that superficially resemble the ERC; we fear that the uniqueness of the ERC program is obscured and needs to be reaffirmed.

The evidence, supported by numerous independent studies, indicates that the ERC program is unique, effective, and efficient. It does important things that are not achievable in any other known manner. It has been instrumental in strengthening our national economic security. The ERC concept, which was always focused on long-term goals, is even more vital to American public interests today than when it was first conceived.

Finally, we wish to offer thanks to the National Science Foundation, companies, staff, administration, students, and all of the other collaborators whose faithful support carried this ERC baby through birth, childhood, and adolescence. It is our hope that all of those "parents" share in the pride that we feel for the accomplishments of the past fifteen years, and that the adult years of the future continue to bring them the satisfaction they deserve for their role in our success.