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New Perspectives on Materials Education in the U.S.

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Graduate and postgraduate education in science and engineering in the U.S. has long been recognized as outstanding. In materials science and engineering, graduate and postgraduate education is not only outstanding, but as a result of its intrinsic multidisciplinary nature, it is having a positive pervasive impact upon the culture within major research universities in the U.S. In spite of this general excellence, new initiatives are being taken to broadly enhance education and training in materials science and engineering, as well as in manufacturing and other areas related to industrial competitiveness. Here we discuss the issues of training modes, undergraduate materials education and research, vocational and "shop floor" level training, as well as some fundamental infrastructure issues that will impact our ability to broadly enhance materials science education in the U.S.

INTRODUCTION

In addition to the traditional support of education through postdoctoral, graduate and undergraduate research within the individual investigator programs and centers, the scientific Directorates and Divisions of the National Science Foundation (NSF) will place an increased emphasis upon curriculum development. In particular, the Division of Materials Research (DMR) will broaden its previous curriculum initiative which focused on materials synthesis and processing.

The scope of materials science and engineering is also such as to make it an excellent paradigm for the study of fundamental concepts of the basic sciences, and their relationship to technology, engineering and manufacturing. The DMR education programs will therefore include the development of courses in materials science and engineering that can be used as general science requirements at the undergraduate level, as well as providing meaningful, hands-on introductions to science and technology at the pre-college level.

In order to stimulate the cross-disciplinary nature of materials research, to provide a vehicle for technology transfer, and to provide expanded opportunities for industry-university interactions, particularly at the individual investigator level, new education programs, linked to industry, have been called for. An Industrial Postdoctoral Program will train new PhDs for materials research and technology development in a competitive, industrial environment. The Industrial Research Assistantship Program will provide graduate research training opportunities, in an industrial setting, and under the joint supervision of a university professor and an industrial scientist, that are the basis of PhD dissertations in materials science and engineering related areas.

TRAINING MODES

Materials research and education is intrinsically multidisciplinary and increasingly interdisciplinary. As a result, a major emphasis has been placed within the National Science Foundation on funding modes that emphasize this type of research and educational environment. Major programs within the Foundation include the Materials Research Laboratory (MRL) Program, the Materials Research Group (MRG) Program, the Science and Technology Centers (STC) Program, the Engineering Research Centers (ERC) Program, and the Industry/University Cooperative Research Centers (IUCRC) Program.

A distinguished 16-member panel, representing academia, foundations, National Labs and large and small businesses, was selected by the Director of DMR in October and November of 1992 to review the MRL and MRG programs. Two members of the National Science Board participated in the deliberations of the panel. The panel was quite explicit in stating that materials science and engineering, unlike many other endeavors, was not a discipline, but rather a field or multi-discipline. As a result, the panel affirmed that the support of multidisciplinary research was the highest priority of DMR. In particular, the panel concluded that the funding priorities were, in order, MRLs, MRGs, and single investigator programs. The essential interdisciplinary character of the MRLs are illustrated in the Tables 1-3:

Research Areas	*No.*
Synthesis and Processing; Novel Materials	7
Phases, Phase Trans., Patterns, Disorder	5
Surfaces, Surface Dynamics and Reactions	5
Thin films, Interfaces, Structural Materials	4
Electronic, Optoelectronic, Optical Materials	5
Polymeric and Macromolecular Materials	8
Superconductivity	4
Materials Theory and Simulation	2
	40

Table 1. MRL Research Thrust Distribution

Academic Departments	*No. PIs*
Chemistry	84
Physics; Appl Physics	105
Materials Science & Engineering	76
Other Engineering	50
Other Science	13
	328

Table 2. MRL Disciplinary Distribution

Resource Type	*No.*
Senior Investigators	328
Post Docs	95
Graduate Students	341
Undergraduates Students	151
Pre-College	19
	934

Table 3. MRL Human Resource Distribution

The average number of academic departments or units involved in the ten (10) MRLs is 6 per MRL. The average number of academic departments or units involved in the eighteen (18) MRLs is 2.3 per MRG. Distribution data for the MRGs are provided in Tables 4-6.

The mode of multidisciplinary, multi-investigator research illustrated, for example, by the MRLs is one of the most important for the US to develop fully. The skill of integrating different disciplines must be taught to students before they become irreversibly enamored of specialization. This teaching can most efficiently (and perhaps only) be done in the atmosphere of the multidisciplinary laboratory. Resultingly, the Panel recommended that:

> *"The National Science Board should take the initiative to develop, with other agencies, a policy that would create a new National network of multidisciplinary laboratories in materials and manufacturing, with adequate financing, and covering a broad range of missions and styles of research".*

Research Areas	*No.*
Solid-St. Chem/Synth/Polymers	4
Structural Materials	3
Magnetics/Magnetic Materials	3
Surface Physics/Chemistry	3
Electronic Materials	2
High Tempt. Superconductivity	2
Diamond/Diamond-like Materials	1
	18

Table 4. MRG Research Thrust Distribution

Academic Departments	*No. PIs*
Physics	48
Materials Science & Engineering	27
Chemistry	19
Other	23
	117

Table 5. MRG Disciplinary Distribution

Resource Type	*No.*
Senior Investigators	117
Post Docs	13
Graduate Students	112
Undergraduates Students	45
	287

Table 6. MRG Human Resource Distribution

The Panel concluded that the multidisciplinary laboratories were relevant to industry. Of particular significance was the role of these laboratories in producing excellent students who are educated to work effectively in multidisciplinary environments and teams. Students with this type of education were deemed crucial in addressing the critical product cycle issue raised in the report of the Special Commission on the Future of NSF.

The materials research and education enterprise, from one perspective, represents an integrating endeavor for the disciplinary derived fundamental activities sustained largely by individual investigators. Although multidisciplinary research and education activities are given high priority, the quality of the multidisciplinary research and education centers will ultimately be determined by the quality of the individual investigators of which they are comprised. Likewise, the return on our investment in national facilities is limited by the skill of the individual investigators who use them.

UNDERGRADUATE MATERIALS EDUCATION AND RESEARCH

The NSF role in undergraduate education is in a state of rapid development because education is becoming ever more closely tied to our activities in research. Our current Federal initiative called the Advanced Materials and Processing Program (AMPP) has a strong educational component. This is especially important, for example, in materials chemistry because the subject is not widely taught in American colleges and universities, and the field is still evolving from elements of solid-state chemistry, polymer chemistry, ceramics science, and the synthesis of functional materials, such as electronic materials.

In order to stimulate curriculum innovations in undergraduate education in materials, NSF convened a workshop in 1989. The recommendations that resulted from it led to the announcement of a new Undergraduate Materials Education Initiative, and six grants were subsequently awarded in fiscal years 1992 and 1993. They have the following foci: materials synthesis and processing as an interdisciplinary activity (Arizona State U., $350,000 for 3 years), interdisciplinary course modules (Iowa State U., $350,000 for 3 years), an undergraduate degree program in the chemistry of materials (Lehigh U., $275,000 for 3 years), the development of a synthesis and processing laboratory course designed to unify concepts of materials science and engineering (MIT, $350,000 for 3 years), a new course emphasizing the development of microstructure in materials (Purdue U., $350,000 for 3 years), and the synthesis and processing of electronic and photonic materials (Wayne State U., $300,000 for 3 years).

In addition to this special activity, NSF encourages the participation of undergraduates through REU (Research Experiences for Undergraduates) grants either to "sites" that permit a group of undergraduates to study a particular subject or to an individual faculty member's regular research grant (REU supplement). These grants provide approximately $5K/yr/student for roughly 10 students/site with an award duration of 1 - 3 years. Currently in materials there are approximately 10 REU sites and 200 REU supplements.

To encourage wider knowledge of the emerging new branch of chemistry called materials chemistry, the Division of Materials Research also provides funds to run summer programs. The very successful program in solid-state chemistry has attracted both undergraduate students and faculty for the past seven years (currently $95,500 per year for 14 undergraduates and 3 faculty members). In this format, participants are first taught the principles of solid-state chemistry, then carry out research at various academic or industrial laboratories, and finally present their results at a symposium.

This year, NSF is also funding a training program in polymer chemistry at three locations, U. of Wisconsin at Stevens Point, U. of Southern Mississippi, and Rensselaer Polytechnic Institute. These summer workshops are designed to familiarize college and university faculty with important concepts in polymer chemistry and to gain hands-on experience with new curricular materials suitable for general and organic chemistry courses.

The Engineering Directorate of the National Science Foundation supports a leveraged program of Engineering Education Coalitions which join a number of engineering schools together to focus on innovative experiments in systemic reform of undergraduate engineering education and educational delivery systems. The Coalitions focus on undergraduate education and have programs of linkages to K-14 educational institutions to stimulate interest in engineering and smooth the transition from community colleges to upperdivision education programs that have undergone reform. The Coalitions focus on curriculum development, implementation, and assessment to determine the impact of the curriculum reform on quality and retention. By focusing on hands-on design and "manufacture" in the freshman years, alternative curricula that emphasize synthesis, production and manufacturing, integrating science and math into engineering topics, and cooperative learning, the Coalitions build skills needed by industry to improve the quality of the engineering workforce and their contribution to competitiveness. Materials science and engineering is an essential component and focus within this framework. This is consistent with the impending incorporation of the AMPP initiative in the more recent Federal initiative in Advanced Manufacturing Technology.

VOCATIONAL AND COMMUNITY COLLEGE TRAINING

DMR and other divisions providing substantial support for materials research and education will respond aggressively to the Scientific and Advanced Technology Act of 1992, which emphasizes the design, development and implementation of highly leveraged programs, focusing on 2-4 year colleges, to reform technical education and training programs.

By late 1993, the National Science Foundation will initiate an educational program to promote exemplary improvement in advanced technological education through support of curriculum development, faculty or teacher enhancement, development of instructional materials, and instrumentation and laboratory improvement, especially for technicians being educated for the high performance workplace of strategic advanced technologies. Supported projects are expected to result in major improvements in advanced technician education, serve as-models for other institutions, yield nationally-relevant educational projects, and have strong evaluation and dissemination components. This new initiative involves collaborative efforts among two-year colleges, four-year colleges and universities, secondary schools, business, industry and government. It is to be noted that one of the new Coalition integrates an innovative program in workforce training in manufacturing with technical college and undergraduate education programs.

It is anticipated that the National Science Foundation approach will yield many dividends: many graduates of two-year college programs will embark immediately on careers in the technical workforce; others will continue their education in pursuit of baccalaureate degrees in technology, science, mathematics, and engineering; and still others will have acquired useful skills and a background in mathematics and science; and bridges between secondary technology education programs and two-year college technician education programs will be built.

The Technology Reinvestment Project (TRP), is an excellent example of a fully cooperative, collaborative venture involving ARPA, NIST, DOE, NSF, and NASA. The goal of TRP is to stimulate the transition to a growing, integrated, national industrial capability which will provide the most advanced, affordable, military systems and the most competitive commercial products. TRP activities fall into three categories:- technology development, technology deployment, and manufacturing education and training. In Fiscal Year 1993, $48.2M of the $471.6M provided under Title IV Appropriations for TRP programs, is for manufacturing education and training activities.

The goals of manufacturing education and training activities, as well as those of technology deployment, included improving the general state of U.S. competitiveness and productivity, and providing a high quality work force for the 21st century. Available funds will be used to provide new manufacturing engineering and training opportunities, including fellowships to reorient and equip defense engineering and commercial technical personnel for the design and manufacturing base of the future. Emphasis is on dual-use engineering skills, and the improvement of technical capabilities at the university, college and vocational levels. The use of experienced manufacturing experts and engineers in classroom settings, as well as structuring of alternative curricula, is included. In addition, support will be provided for workforce training centers linking universities, technical colleges, community colleges and industry to focus on curricula needed to advance the technical skills of the workforce and the production skills of the engineers.

The workforce of the near term future (the next five to ten years) will be even more technologically challenged than the workforce of today. Closer partnerships between and among the education and academic communities, and all components of the business sector will be required if we are to meet these future needs and challenges.

INFRASTRUCTURE PERSPECTIVES

Instrumentation and equipment is a key to, and a major driver for, innovative research and development. Instrumentation and equipment determine what experimental research can be viably pursued and the level of productivity that can be sustained in these pursuits. For example, they determine our ability to synthesize and to process advanced materials, as well as our ability to monitor, and therefore to control, such synthesis and processing in both the laboratory and manufacturing environment.

A major challenge facing the Foundation is the wider deployment of advanced research instrumentation and equipment. Wider deployment is needed to quicken the pace of scientific and technological breakthroughs, for example, in the synthesis and the processing, and ultimately in the manufacturing, of advanced materials. Wider deployment for research would also have a profound effect on the research based component of both graduate and undergraduate education. More generally, the wider deployment of advanced research instrumentation and equipment could enhance the educational opportunities and experiences at a broader range of institutions. This is particularly significant with the increasing recognition of the need to strengthen technical education programs at the baccalaureate level, as well as within the curricula of two-year community colleges and technical schools.

There are many impediments to the wider deployment of advanced research instrumentation and equipment. These include potentially spiraling costs, both capital and operating, as well as design complexities which makes reliability low, maintainability difficult, and virtually necessitates the kind of general facilities support infrastructure that can only be maintained in our larger research universities. These impediments are tied, to a large extent, to *the way we develop equipment*. Performance has been virtually the sole driver of instrumentation and equipment design, particularly in the limited competitiveness of today's market. Another factor is that the design of much of our advanced research instrumentation and equipment tends to be of the *over-the-wall type*. That is, the designs consist predominately of the *repackaging* of instruments developed by bench scientists. In these instances, the *manufacturing engineering value-added is minimal.*

There is much to be gained by the reversal of the current advanced research instrumentation and equipment development approach, which unchecked, will likely continue to lead us along the ever-increasing cost spiral viewed as inevitable by many. Design, development and manufacturing processes for advanced research instrumentation and equipment can be structured to yield products that are optimized over a much larger set of simultaneous objectives. Such a set might include enhanced performance (e.g., accuracy, resolution, capacity, throughput, etc.), friendlier user interface, flexible operation and applicability, higher reliability, improved maintainability, as well as lower cost (both capital and operating). Most of these attributes relate directly to the general goal of wider deployment.

NSF is taking the initiative in stimulating the development of the next generation of advanced research instrumentation and equipment according to a new paradigm. This paradigm consists of the close collaboration between bench scientists who are specialists in particular instrumentation areas and experts in the area of advanced manufacturing technologies working together within the framework of concurrent engineering. It is this approach that will *maximize the manufacturing engineering value-added*. Manufacturability must become an up-front consideration. A collaborative concurrent engineering framework provides a systematic and rational method for establishing research and development priorities in support of advanced research instrumentation and equipment development.

CONCLUDING REMARKS

The scientific Directorates at the National Science Foundation will become more intimately involved in education, including materials education, at all levels. Multidisciplinary research programs will be evaluated, in part, by their impact upon the multidisciplinary education culture within the host university. There is an increased awareness of the roles of the scientific Directorates in education at the undergraduate and vocational levels, and its relevance to enhanced economic competitiveness. The U.S. faces a period of challenge and opportunity. I predict that the decade of the 90's will be one of innovation in education, particularly in manufacturing and materials.