TITLE:

21st Century Engineering: A Roadmap to the Future

PRINCIPAL INVESTIGATOR:

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PROJECT SUMMARY:

An array of powerful forces including demographics, globalization, and rapidly evolving technologies are driving profound changes in the role of engineering in society. The growing awareness of the importance of technological innovation to economic competitiveness and national security is demanding a new priority for application-driven basic engineering research. The changing workforce and technology needs of a global knowledge society are changing dramatically the nature of engineering practice. Moreover, new challenges such as "off-shoring", immigration restrictions, and inadequate diversity in the domestic engineering workforce are also raising serious questions about the adequacy of our current approach to engineering education, both in terms of pedagogy and in our capacity to tap the talents of underserved populations for engineering careers.

This project will explore new paradigms for engineering research, education, and practice that address the needs of a 21st century global, knowledge-driven society. A multi-stakeholder team of technology leaders will be used as a guidance group in the development and assessment of new visions for the future of engineering, using a combination of workshops and interviews. The project will evaluate recent efforts both in the United States and abroad to rethink various aspects of engineering research, education, and practice, both to inform the visioning effort, and to harvest those aspects that align most clearly with new visions for engineering in America. In particular, it will link an action agenda to recent efforts such as the NAE's Committee to Assess the Capacity of U.S. Engineering Research and the Engineer of 2020 study, the Council on Competitiveness's National Innovation Initiative, and the NSF's Cyberinfrastructure Report. A road-mapping framework will be developed for moving toward these visions, coordinating closely with parallel efforts from other groups such as the National Academies, the federal government, higher education, and industry. Initial steps will be taken to build the necessary awareness and support among leaders in government, industry, and education sectors. Particular attention will be paid to developing bolder and more effective efforts to attract broader segments of our population into careers in engineering.

<u>Intellectual contributions</u>: This project will explore at the most fundamental level the changing character of engineering research and practice that is likely to drive a revolution in engineering education. The increasingly interdisciplinary character of research, coupling investigations at the microscopic level (e.g., info-bio-nano) with the complex systems characterizing our global society (e.g., energy and global sustainability); the shift from analysis (now increasingly facilitated by information technology) to synthesis, creativity, and innovation as the primary activities of engineers; and the rapidly changing nature of advanced education (e.g., lifelong, collaborative, interactive, and ubiquitous) are examples of intellectual issues to be studied in this project.

<u>Broader impact</u>: This project will address one of the most critical issues facing our nation: how to generate the new engineering knowledge and human resources necessary to sustain the nation's leadership in technological innovation so key to our future prosperity and security. This project will develop a roadmap proposing a vision and suggesting necessary public and private investments in engineering research, practice, and education. It will also take steps to build the necessary level of understanding and support for achieving this vision, so critical to the future of our nation.

PROJECT DESCRIPTION:

Background

We live in a time of great change, an increasingly global society, driven by the exponential growth of new knowledge and knitted together by rapidly evolving technologies. It is a time of challenge and contradiction, as an ever-increasing human population threatens global sustainability; a global, knowledge-driven economy places a new premium on technological workforce skills through phenomena such as off-shoring; governments place increasing confidence in market forces to reflect public priorities even as new paradigms such as open-source software challenge conventional free-market philosophies; and shifting geopolitical tensions are driven by the great disparity in wealth and power about the globe, manifested in the current threat to homeland security by terrorism. Yet it is also a time of unusual opportunity and optimism as new technologies not only improve the human condition but also enable the creation and flourishing of new communities and social institutions more capable of addressing the needs of our society. Both these challenges and opportunities suggest that major changes will be necessary in engineering research, education, and practice in the century ahead that go far beyond conventional paradigms.

Engineering Research

There is increasing recognition that leadership in technological innovation will be key to the nation's prosperity and security in a hypercompetitive, global, knowledge-driven economy. (National Innovation Initiative, 2003) While our American culture, based upon a highly diverse population, democratic values, and free-market practices, provides an unusually fertile environment for technological innovation and entrepreneurial activity, history has shown that significant federal and private initiatives are necessary to produce the essential ingredients necessary for innovation to flourish: new knowledge (research), human capital (education), infrastructure (e.g., physical, cyber), and policies (e.g., tax, property) for innovation to flourish. Other nations are beginning to reap the benefits of such investments aimed at stimulating and exploiting technological innovation, creating serious competitive challenges to American industry and business both in the conventional marketplace (e.g., Toyota) and through new paradigms such as the off-shoring of knowledge-intensive services (e.g. Bangalore).

One of the most critical—and today most neglected—elements of the innovation process is the long-term research required to transform new knowledge generated by fundamental scientific discovery into innovative new products, processes, and services required by society. In years past this applications-driven basic research, sometimes referred to as Pasteur's Quadrant (Stokes, 1997; Sonnert, 2002), was a primary concern both of major corporate R&D laboratories and campus-based programs such as engineering schools. However in today's world of quarterly earnings pressure and inadequate federal support of research in the physical sciences and engineering, this longer-term, applications-driven basic research has largely disappeared both from the corporate setting and from the campuses, putting at risk the discover-innovation process in the United States.

Numerous recent studies (Duderstadt, 2004; Duderstadt, 1998-03; Clough, 2002; Vest, 2003) have concluded that stagnant federal investments in basic engineering research, key to technical innovation, are no longer adequate to meet the challenge of an increasingly competitive global economy. There is further evidence that the serious imbalance between federally supported research, now amounting to less than 26% of national R&D, along with the imbalance that has resulted from the five-fold increase in federal support of biomedical research during a period when support of research in the physical sciences and engineering has remained stagnant, threatens the national capacity for innovation.

Engineering Practice

The rapid evolution of high quality engineering services in developing nations with significantly lower labor costs such as India, China, and the Eastern Bloc nations raises a serious question about the global viability of the United States engineer, who must now produce effectively three times the value-added to justify wage differentials. Both new technologies (e.g., info-bio-nano) and the complex systems problems arising in contemporary society require highly interdisciplinary engineering teams rather than practice within the traditional disciplines. The globalization of markets requires engineers capable of working in multinational corporations and NGOs. New perspectives are needed in building competitive enterprises as the distinction between competition and collaborator blurs. A projected 21st century world population of 8 to 10 billion strains the limits of the planet, endangers the global climate, and threatens major losses in biological and cultural diversity. As technological innovation plays an ever more critical role in sustaining the nation's economic prosperity, security, and social well-being, engineering practice will be challenged to shift from analytical problem solving more toward creative and novel solutions while considering an array of social, environmental, cultural, and ethical issues.

Engineering Education

In view of these changes being driven in engineering research and practice, it is easy to understand why some maintain that today's engineering educators are utilizing 19th century methods in 20th century institutions to produce engineers for a 21st century world. Clearly new paradigms for engineering education are demanded to: i) respond to the incredible pace of intellectual change (e.g., from reductionism to complexity, from analysis to synthesis, from disciplinary to multidisciplinary); ii) develop and implement new technologies (e.g, at the microscopic level of info-bio-nano or the macroscopic level of global systems); and iii) accommodate a far more holistic approach to addressing social needs and priorities, linking social, economic, environmental, legal, and political considerations with technological design and innovation.

The critical role of our engineering schools in providing human capital necessary to meet national needs faces particular challenges. (Clough, 2003; Duderstadt, 2004) Student interest in science and engineering careers is at a low ebb. Cumbersome immigration policies in the wake of 9-11 along with negative international reaction to U.S. foreign policy is threatening the pipeline of talented international science and engineering students into our universities and engineering workforce. Furthermore, it is increasingly clear that a far bolder and more effective strategy is necessary if we are to tap the talents of all segments of our increasingly diverse society.

The current paradigm for engineering education, e.g., an undergraduate degree in a particular discipline, perhaps augmented with further graduate or professional studies, seems increasingly suspect in an era in which the shelf-life of taught knowledge has declined to a few years. Perhaps engineering should take a more formal approach to lifelong learning, much as have other professions such as medicine in which the knowledge base has overwhelmed the traditional educational process. Our engineering science-dominated curricula need to be broadened considerably if we are provide students with the opportunity to learn the innovation and entrepreneurial skills so essential for our nation's economic welfare and security. As technology becomes an ever more dominant aspect of social issues, perhaps engineering education should evolve more along the lines of other academic disciplines that have become cornerstones of the "liberal arts cannon". Perhaps the most urgent need of our society is a deeper understanding and appreciation for technology on the part of all college graduates rather than simply those seeking engineering degrees. These, too, should be concerns of engineering educators.

Project Objectives

The objectives of the project are as follows:

1. To expand the solution space of possible new paradigms for engineering research, education, and practice in the United States by harvesting the ideas of a network of thought leaders from industry, government, and engineering education—that is, from both producers and the consumers of innovative technology and well-trained engineers (i.e., research and human capital) as well as the experience of earlier efforts aimed at improving engineering research, education, and practice both in this nation and abroad.

2. To analyze the results and experiences of various past and current efforts to explore new engineering paradigms (e.g., the NSF Engineering Research Centers, the NSF Systemic Initiatives, the NAE Engineer of 2020 Project (Clough, 2003), and novel experiments such as the Olin College of Engineering), within a framework that addresses future national and global needs.

3. To develop a roadmap for implementing new strategies for engineering research, education, and practice, that will involve new public and private investment, policy development, and institutional transformation (within government, industry, and higher education).

4. To suggest strategies for more effectively tapping the talents of those segments currently underrepresented in the engineering profession (drawing on successful models of achieving and defending diversity in other areas of higher education).

5. To link this project closely to current studies such as the NAE Committee to Assess the Capacity of the U.S. Engineering Research Enterprise (Duderstadt; 2004), the Council on Competitiveness' National Innovation Initiative, and the NSF Cyberinfrastructure Initiative (Atkins, 2003), which provide excellent opportunities to build strong support for the necessary public and private actions that will be necessary to achieve the goals of these studies that benefit engineering research, education, and practice.

6. To undertake the early stages necessary to launch this agenda, through stimulating awareness of both challenges and opportunities, building networks linking together key stakeholders, and engaging leadership groups such as the National Academies, professional societies, industrial groups and engineering education.

Project Design

Although in one sense the proposed project will provide the follow-on action agenda for engineering research, education, and practice linked to ongoing studies (see above), it will also have a deeper and broader intellectual goal of rethinking the very nature of engineering research, education, and practice in light of several of the important changes occurring in our world today–e.g., the changing nature and importance of technological innovation; the impact of rapidly evolving cyberinfrastructure; the shifting and ever-more tightly integrated nature of the various engineering and scientific disciplines; the broadening of engineering practice (and hence the need for engineering education) to consider the economic, social, and environmental nature of complex engineering systems; and the changing nature of the engineering workforce).

Rather than simply conducting a study and delivering a report, a key objective of this project is to stimulate action necessary to enhance the support and possibly transform various aspects of engineering research, education, and practice. The elements of the project include the following:

1. An assessment of both past and ongoing efforts to transform aspects of engineering research, education, and practice into activities more aligned with the needs of a 21st century, global, knowledge-driven society. This would involve literature surveys and interviews with key leaders of these activities. We also to develop an intellectual architecture to link and evaluate these various activities.

2. The formation of a team or "project guidance group" (in the language of the National Academies) of leaders in engineering and technology from industry, government, higher education, and the engineering profession to reconsider the most fundamental aspects of engineering research, education, and practice within the context of a changing world. This group would be challenged to develop bold visions and action plans that push beyond the envelope of both existing practice and current speculation. More specifically:

    - The team would consists of roughly two dozen leaders with broad representation from the National Academies, industry, higher education, professional societies, federal agencies, as well as a representation reflecting the diversity of the future engineering workforce.

    - Although most of the activities of the guidance team would be through Internet-based collaboration, teleconferences, and subgroup assignments, each year the entire team would be assembled in Ann Arbor for a two day workshop to review progress and guide future activities.

    - During the first year the activities of the group would be focused on developing new visions for the future of engineering, informed by the inventory mentioned in Item 1, and begin the development of action plans (roadmaps) aimed at moving toward these visions.

    - In the second year members of the team would work closely with the project director in taking key steps toward implementing the action plan.

    - The third and final year of the project would involve further execution of the action agenda by the guidance team as well as providing an assessment of progress toward goals and a refinement and development of further strategies.

3. Several examples of the possible visions that suggest the scope of the project include:

- A strategy for addressing the growing imbalance in federal research investments among the various disciplines that has led to stagnation in physical science and engineering over the past three decades relative to a six-fold growth biomedical research.

- The exploration of a bold federal initiative, similar to the Land-Grant Acts of the 19th century, which would create major federally funded "discovery-innovation institutes" on university campuses aimed at supporting long-term engineering research and bridging the gap between scientific discoveries and technological innovation.

- The development of a strategy to address the implications of rapidly evolving cyberinfrastructure for engineering, as we approach an inflection point in the potential of rapidly evolving information and communications technology to transform how the scientific and engineering enterprise does knowledge work, the nature of the problems it undertakes, and the broadening of those able to participate in research activities.

- The study of new research paradigms that are more capable of responding to the highly nonlinear nature of the development and transfer of knowledge from fundamental scientific inquiry through engineering research and technological innovation into social applications.

- Drawing on earlier experience in successful diversity efforts in higher education (e.g., the Michigan Mandate, Duderstadt, 2000) to develop and promote implementation of a more effective strategy to build an engineering workforce that more adequately reflects the growing diversity of the American population.

- A serious examination of whether the current paradigm of engineering education and practice in the United States (e.g., primarily viewed as a undergraduate professional program) is viable in the face of explosive growth in knowledge and increasingly intense global competition (e.g., off-shoring) enabled by robust communications technologies. This could be analogous to the Flexner Report, which completely restructured both medical education and the medical profession itself a century ago.

4. Working closely with the guidance team, the project would develop a roadmap of both strategies and actions aimed at moving toward these visions. This would involve not only the distribution and propagation of the ideas of the visioning effort, but also an effort to stimulate awareness among various stakeholder groups (industry, federal agencies, engineering education, professional societies) and, hopefully, to build support for an action agenda.

5. Such activities would involve extensive communications activities by the project director both through personal contacts and broader communications activities (websites, lectures, reports, white papers, and perhaps books). Key in this activity would be access to a network of relationships with key leaders in both the public and private sector that the project director has built over the past two decades of active leadership in both higher education and the science and engineering communities (see biography). Comprehensive annual reports on key

findings and actions undertaken by the project would be prepared and circulated broadly within the engineering community to stimulate awareness and invite feedback.

6. Utilizing the guidance team to assess the effectiveness of both strategies and early efforts to move toward key visions of 21st century engineering research, education, and practice, accompanied by an effort to mainstream the more successful efforts so that they continue past the conclusion of the project.

Concluding Remarks

While many have stressed the importance of engineering research, education, and practice to a nation ever more dependent on technological innovation in a global, knowledge-driven society, most efforts to develop new visions for the profession have remained relatively close to the status quo. Yet at a time when disruptive technologies are driving rapid, profound, and unpredictable change in most social institutions in the public and private sector, it is logical to suggest that perhaps more radical options should be considered. This is the key objective of the proposed project, to break out of the box of conventional thinking, and to develop and promote new visions of engineering, in all its manifestations and applications, for a 21st century world, and then to take the first steps toward moving toward such visions.

REFERENCES:

Daniel E. Atkins, Chair, *Revolutionizing Science and Engineering through Cyberinfrastructure*, Report of the National Science Foundation Advisory Panel on Cyberinfrastructure (National Science Foundation, 2003)

Wayne Clough, Chair, *The Engineer of 2020: Visions of Engineering in the New Century, National Academy of Engineering*, Washington, 2003

Wayne Clough, Chair, *Assessing the U.S. R&D Investment, President's Council of Advisors on Science and Technology*, October, 2002.

James J. Duderstadt, *A University for the 21st Century* (University of Michigan Press, Ann Arbor, 2000) pp. 192-219.

James J. Duderstadt, Chair, "Observations on the President's Fiscal Year Federal Science and Technology Budget", COSEPUP (National Academy of Sciences, Washington, 1998-2003).

James J. Duderstadt, Chair, NAE Committee to Assess the Capacity of the U. S. Engineering Research Enterprise (report to appear in early fall, 2004).

National Innovation Initiative, Council on Competitiveness, 2003, http://www.compete.org/nii/

G. Sonnert and G. Holton, *Ivory Bridges: Connecting Science and Society*, MIT Press, Cambridge, 2002.

Donald E. Stokes, *Pasteur's Quadrant: Basic Science and Technological Innovation* (Brookings Institution Press, Washington, D.C., 1997).

Charles M. Vest, Chair, "Report of the Task Force on the Future of Science Programs at the Department of Energy", U.S. Department of Energy, Washington, 2003.

BIOGRAPHICAL INFORMATION: James Johnson Duderstadt

Professional Preparation

Yale University	Electrical Engineering	B. Eng.,1964
Caltech	Engineering Science	M.S., 1965
Caltech	Engineering Science & Physics	Ph.D., 1967
Caltech	A.E.C. Postdoctoral Fellow	1968

Appointments

Academic (all at the University of Michigan, Ann Arbor)

University Professor of Science and Engineering, President Emeritus, 1996 –
Director, Program in Science, Technology, and Public Policy, 2003 –
Director, Millennium Project, 2003 –
President, 1988 – 1996
Provost and Vice President for Academic Affairs, 1986 – 1988
Dean of the College of Engineering, 1981-1986
Professor of Nuclear Engineering, 1976-86; AP, 1972-76; aP, 1969-72

Other Major Appointments

National Science Board (1985-1996): Chair (1991-1994)
National Academy of Engineering, Executive Council (1993-2001)
COSEPUP, National Academies (1997-2003)
Nuclear Energy Research Advisory Committee, Chair (1998-2002)
Chair or member of numerous National Academies committees

Publications

James J. Duderstadt, Chair, "Observations on the President's Fiscal Year Federal Science and Technology Budget", COSEPUP (National Academy of Sciences, Washington, 1998-2003)
James J. Duderstadt, Chair, *Preparing for the Revolution: Information Technology and the Future of the Research University*, NRC (National Academy Press, Washington, 2002)
James J. Duderstadt, Douglas van Houweling, Daniel Atkins, *Higher Education Faces the Digital Age* (Praeger Publishers, ACE, 2002)
James J. Duderstadt, *A University for the 21st Century (University of Michigan Press*, Ann Arbor, 2000)
James J. Duderstadt, G. F. Knoll, and G. S. Springer, *Principles of Engineering* (John Wiley and Sons, New York, 1982)

Other Significant Publications

James J. Duderstadt and Luc Weber, Eds., *Reinventing the Research University* (Economica, London, 2004); see also "The Changing Nature of Research and the Future of the Research University", pp. 15-28

James J. Duderstadt and Farris W. Womack, *The Future of the Public University in America* (Johns Hopkins University Press, Baltimore, 2002)

James J. Duderstadt and Gregory A. Moses, *Inertial Confinement Fusion* (Wiley-Interscience, New York, 1982)

James J. Duderstadt and William R. Martin, *Transport Theory* (Wiley-Interscience, New York 1979)

James J. Duderstadt and Louis J. Hamilton, *Nuclear Reactor Analysis* (John Wiley and Sons, 1976)

Synergistic Activities

Co-chair (with William Wulf) of the IT-Forum of the National Academies (an effort to understand impact of IT on research and education)

National Medal of Technology, 1991 ("For his excellence in the development of strategies for engineering; and for his success in bringing women and minorities into the nation's technological workforce"); Also architect of the Michigan Mandate, the successful effort to double minority representation of students and faculty (leading to 2003 Supreme Court decision in Michigan cases)

Member of numerous National Academies bodies (e.g., NAE Executive Council, COSEPUP) and chair of various committees concerned with research and education in science and engineering

Past member of numerous NSF bodies concerned with similar issues (e.g., NSB, ACEHR, NSB EHR Subcommittee)

Chair, Nuclear Energy Research Advisory Committee, DOE, developing strategies for rebuilding research capability and human resources in nuclear energy

Collaborators and Other Affiliations

National Academy Panels
- Co-Chair with William Wulf, President of NAE

Book Co-authors of past four years
- Daniel E. Atkins, University of Michigan
- Douglas van Houweling, President, Internet2

NSF Grant Co-investigators
- Michael Corradini, University of Wisconsin
- William Martin, University of Michigan

Ph.D. Advisor: Harold Lurie (Caltech); Postdoc Spon: Noel Corngold (Caltech)

Thesis Advisor: 22 Ph.D.s, 30 M.S. (all prior to 1980)

Other affiliations: Board of Directors: Unisys Corporation, CMS Energy

BUDGET: See documentation

CURRENT OR PENDING SUPPORT:

Atlantic Philanthropies Grant 9193: "Education in the Digital Age: Leadership, Linkages, and Roadmaps"
Principal Investigator: James J. Duderstadt
Total Grant: $876,000 (3 years)
Grant Period: 1/1/01 to 12/31/04

Recent NSF Grants:
NSF Grant 0129712: Development of an Undergraduate Minor Concentration in Nuclear Fission power Engineering (EEC-Small Grants for Exploratory Research)
Principal Investigators: James J. Duderstadt, University of Michigan
William R. Martin, University of Michigan
Michael Corradini, University of Wisconsin
Grant Amount: $100,000 (1 year)
Grant Period: 8/31/2001 to 8/31/2002