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THE NATIONAL ACADEMIES

National Academy of Sciences
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Editorial

George Bugliarello is chancellor, Polytechnic University, and interim editor-in-chief of The Bridge.

Balance!

We have reached a critical point in the vertiginous march of technology. In the space of a few decades, what were only fantasies or science fiction have begun to become reality, from humans walking on the Moon to machines replacing diseased organs to engineered modifications of life. These engineering and scientific triumphs, immense as they are, are but embryos of what human ingenuity and organization undoubtedly will be able to do in the future. Yet, the very thought of what these future developments may portend for our species is also engendering concerns—not only among a general public not versed in engineering and science, but also among engineers and scientists.

In a recent article, Bill Joy, chief scientist of Sun Microsystems, wrote that he sees our future as one in which "our most powerful twenty-first century technologies—robotics, genetic engineering and nanotech—are threatening to make humans an endangered species" (*Wired* 8.04). His concern is but the latest chapter in a series that has its beginnings in the unfathomable depths of our sentient past. The Greeks of the classical age bemoaned the disappearance of a mythical golden age of peace and harmony between gods—the source of all that was good—and humans. At the end of the first millennium of the common era, Europe feared the end of the world and the advent of the final judgement. The massacres of World War I destroyed the optimism that had stemmed from the enormous technological progress of the previous hundred years. In World War II, Oppenheim and some other creators of the atom bomb—a few still with us—recoiled from the stupendous force they had unleashed. But, if Bill Joy's concerns are not new, they address new, powerful, and pervasive technologies. Engineers should not dismiss them lightly, or ignore the reasons behind the recurring sense of foreboding that continues to accompany some technological and scientific advances. To be sure, only a small minority of our species harbor that sense—but also, to be sure, only a minority view the future without ever removing their rose-colored glasses.

Engineers, by definition, are creators of machines and modifiers of nature. These two tasks are so heady, and today's engineering achievements would have appeared so godlike to humans of earlier societies, that the temptations of technological determinism—of the "if it can be done, it shall be done"—are real. It is the danger of these temptations, quite evident in the development of nuclear weapons, that is at the root of today's fears about the future of our species.

Even aside from the threat of weapons of mass destruction, there are new worries about long-term threats to our survival caused by the accelerated depletion of natural resources, our stressed ways of life, injuries to the environment, and the destruction of other species. These, in different ways, are concerns of citizens of an affluent society just as much as of those of a poorer one.

But the avoidance of technological determinism and the amelioration of the human condition demand the intelligent societal use of technology, not the proscribing of scientific and technological advances. The consequences of today's engineering achievements are far from unidirectional or preordained. The reversal of trends—exemplified by the reduction of noxious car emissions, by the cleaning of rivers, and by the efforts in international arms control—are good beginnings, even if still too limited, even if we continue to drive gas guzzlers or sell weapons.

Thus, if, on the one hand, one can always hypothesize terrifying catastrophes, on the other hand one must also reflect upon the enormous enhancement of our humanity that engineering has made and will continue to make possible. The nations caught in the maelstroms of World War I and World War II recovered quite fast, and no nuclear weapon has been exploded in anger since Nagasaki. The free market industrial nations have enjoyed enormous increases in life expectancies and living standards thanks to new infrastructures, new industries, and new technologies. And, for the first time since the beginning of life on Earth, a living organism—man—can evade the prison of Earth's gravity and the tyranny of evolution, and is not trapped by geography, having learned to communicate all over the globe.

These enhancements of our biological reach and our society are the yin of promise to the yang of fear of technology. Clearly, the promise is far from being universally believed, when half of humankind is still denied even the simplest benefit of technology, from food to housing, to sanitation, to health. But still that half hopes for advances that will improve its lot, advances that can only come from being able to receive the benefits of technology, and from being able to participate in the global economy that makes the other half affluent. There is a profound difference between the hope that says "we need more and better technology that is better distributed," and the fear that says "stop."

The hope to improve the lot of the poorer half of the world lies squarely in making available to them the fruits of technology, in having new technologies bypass older ones that would be impossibly costly or inadequate. The hope for all, affluent and poor alike, should be for technologies that will free humans from degrading and dangerous work, that will create new jobs and make possible better distribution systems for food and services. And the hope should be for the development of a global hyperintelligence through the combined prowess of individuals, societies, and machines that would stamp out the foolishness of today's conflicts and extend to every human being the fruits of the creativity of engineers. Those fruits go beyond the material, the tangible, as they make possible a new vision of what it means to be human.

These are not utopian but real possibilities that depend first and foremost on engineers holding a balanced view of the promise—as well as of the pitfalls—of technology. To be sure, there is no certainty, but this is not a reason for engineering to retreat.

George Bugliarello

Earth Systems Engineering: The World As Human Artifact

Brad R. Allenby

Managing the Earth's complex systems and their dynamics is the next great challenge for the engineering profession.

Brad Allenby is vice president of environment, health and safety at AT&T and adjunct professor, Columbia University School of International and Public Affairs.[1]

The Earth is increasingly a product of human engineering. Up until very recently, however, this engineering process has occurred without conscious recognition; it consists of the sum of human activities, grown to scales unprecedented in the history of the globe. A myriad of economic and engineering decisions, evaluated and taken as if independent, are in reality tightly coupled both to each other and to underlying natural systems. Anthropogenic climate change; loss of biodiversity and critical habitat; degradation of soil, water, and air resources; dispersion of toxic metals and organics—these are the fruits of human engineering just as surely as the computer, the automobile, and the highway infrastructure.

In many cases, these effects are unintended, but they are, nevertheless, the direct results of human activity and design. For example, virtually all island communities suffer from invasive species, introduced by humans, and the resulting extinction of indigenous species—a process that resulted directly from the growth of transportation technologies that accompanied the industrial revolution, the growth of capitalism and global markets, and the expansion of the European culture around the world.

Developing the capability to engineer at the level of global systems—from energy, transportation, and information systems to the carbon and nitrogen cycles—is the next great challenge for engineering. This "Earth systems engineering" (ESE) capability will not replace traditional engineering disciplines, but will augment them. However, to address the complexities and dynamics of global systems, it will require a fundamentally different way of engineering (Allenby, 1999a).

We must begin by recognizing a basic, if disconcerting, truth: the Earth, as it now exists, is a human artifact. It reflects the (frequently unintended and unconscious, but nonetheless real) design of a single species.

The intellectual tools that conscious ESE will require are not yet available.

Although this process has been accelerated by the industrial revolution, "natural" and human systems at all scales have in fact been impacting each other and co-evolving together for millennia, and they are now more tightly coupled than ever.

Copper production during the Sung Dynasty, as well as in Athens and the Roman Republic and Empire, is reflected in deposition levels in Greenland ice (Hong et al., 1996). And lead production in ancient Athens, Rome, and medieval Europe is reflected in increases in lead concentration in the sediments of Swedish lakes (Renberg et al., 1994). The buildup of carbon dioxide in the atmosphere began not with the post-World War II growth in consumption of fossil fuel, but with the deforestation of Europe, Africa, and Asia over the past centuries and millennia (Jager and Barry, 1990). Humanity's impacts on biota, both directly through predation and indirectly through the introduction of new species to indigenous habitats, has been going on for centuries as well (Jablonski, 1991).

What is striking today is the discontinuity between the relatively minor and localized impacts of human activity which predominated before the industrial revolution, and the global, systemic impacts which now characterize the interrelationships between human activity and fundamental biological, physical and chemical systems (Ehrlich and Wilson, 1991; Turner et al., 1990; *Science,* 1997).

The issue, then, is not whether we should *begin* ESE, because we have been doing it for a long time, albeit unintentionally. The issue is whether we will assume the ethical responsibility to do ESE rationally and responsibly. The challenges are substantial, and the intellectual tools that conscious ESE will require are not yet available. Some of the requisite capabilities are beginning to develop in the new multidisciplinary field of industrial ecology and the scientific work on global climate change issues, but there must be parallel progress in relevant social sciences, as well as the development of appropriate institutional, ethical, and policy structures. To a large degree it is in these latter areas, heavily imbued with religious and cultural values, where awareness of the challenge is lowest and the barriers to change are most substantial (Allenby, 1999b).

Conceptually, Earth systems engineering may be defined as the study and practice of engineering human technology systems, and related elements of natural systems, in such a way as to provide the required functionality while facilitating the active management of the dynamics of strongly coupled fundamental natural systems. Such fundamental natural systems might include, for example, the grand elemental cycles (e.g., the carbon, nitrogen, and sulfur cycles), critical habitats, and atmospheric or oceanic systems. Minimizing the risk and scale of unplanned or undesirable perturbations in such systems is an obvious ESE objective.

Engineering Human and Natural Systems

It is worth noting that, given the tight coupling between human and natural systems, engineering and managing elements of both might well be required. Thus, for example, response to droughts might include not just hydrological projects, but also bioengineering of salt-tolerant agricultural species. But an important caution must also be borne in mind—hubris and concomitant premature manipulation of critical natural systems are real potential dangers. If we were not already damaging these complex systems unintentionally, we should not dare to try to engineer them intentionally. But existing impacts and extinctions are real, and the domination of critical systems' dynamics by humans is real, if unintended. Under these circumstances, it would be irresponsible, verging on unethical, not to begin developing the capability for sophisticated ESE.

Examples of Earth Systems Engineering

Once we recognize that human and natural systems have been coupled in a meaningful way for centuries, it is relatively easy to see examples of Earth systems engineering in the past, and potential examples for the future. The principle differences between the historical and the proposed are two: one of scale and one of intent. In the past, Earth system engineering projects were in general more local, and had less global impact. This, of course, reflects the more local scale of human population levels and activity—only loosely coupled over regional areas, and uncoupled at the global scale—that tended to dominate at the time (Turner et al., 1990). Second, to the extent that a set of independently initiated human activities gave rise to "emergent characteristics" at regional or global levels, they tended to be unanticipated and unintended. It is the scale and intent that differentiate ESE from existing engineering disciplines.

Consider, for example, the case of the Aral Sea, a classic example of unintended impacts. Actually a lake, the Aral Sea straddles the borders of Kazakhstan and Uzbekistan. Only decades ago it was the fourth largest lake in the world, but in a few short years it has lost about half its area and some three-fourths of its volume because of the diversion of 94 percent of the flow of two of its feeder rivers, the Amu Darya and the Syr Darya. The purpose of the diversion was primarily to grow cotton, but ironically, the resulting irrigation system is extremely inefficient. Some estimates are that only 30 percent of the diverted water, carried in unlined canals through sandy desert soils, reaches its destination.

The unintended results of this engineering project are staggering—the desertification of the region (the resulting Ak-kum desert, expected to reach 3 million hectares this year, did not even exist 35 years ago); the generation of some 40 to 150 million tons of toxic dust per year with substantial detrimental impacts on regional agriculture and human health; potential impacts on the climate regimes of China, India, and southeastern Europe; the increased salinization of the Aral Sea which resulted in the loss of 20 of its 24 fish species and a drop in the fish catch from 44,000 tons in the 1950s to zero today (with a concomitant loss of 60,000 jobs); the reduction in nesting bird species in the area from 173 to 38; and possibly the release of biological warfare agents previously contained because they were quarantined on an island (Voskreseniye Island) which is now becoming a peninsula (Postel, 1996; Feshbach, 1996).

The most obvious initial observation is that this case study is archetypal. Such water management activities have been going on for centuries, frequently with unanticipated or undesirable impacts, and often with significant political implications. For example, in ancient China, massive irrigation projects were a signature of, and a major co-evolved institution supporting, the development of highly organized feudal power as far back as the Chin state in the Wei River valley some 2,300 years ago (Needham, 1954). Indeed, such impacts arise not just from individual projects, but from water management regimes taken as a whole, often combined with other anthropogenic activities.

To take an example from North America, data from the Nature Conservancy indicate that, apart from extinctions that have already occurred, 36 percent of freshwater fish species, 38 percent of amphibians, 50 percent of crayfish, and 56 percent of mussel species are in jeopardy in the United States, not usually considered a center of extinction activity. The three main forcing functions for this impact on aquatic biodiversity are agriculture, dams, and exotic species—all anthropogenic causes (Doyle, 1997).

ESE approaches have begun to evolve in the area of global climate change research.

One area where ESE approaches have begun to evolve, albeit in an ad hoc manner, is in the area of global climate change research and the development of potential geoengineering responses. An example of this genre is the idea of shifting fossil fuel power plants, the perennial "bad guy" contributing to climate change, to become an important component of an engineered carbon cycle management system. The technology involved is conceptually simple: carbon dioxide resulting from fossil fuel combustion in power plants is captured and sequestered for centuries in deep aquifers, the ocean, geologic formations, or other reasonably long-term sinks.

Many of the technologies currently exist to capture the carbon dioxide emissions and inject them into various sinks, and, especially if carbon capture is implemented at the initial design stage rather than retrofitted, such systems appear to be technologically and economically feasible (Socolow, 1997). For example, Norway's state-owned petroleum company, Statoil, is currently sequestering the carbon dioxide content of the natural gas it is extracting from the Sleipner gas field off the coast of Norway back into an aquifer about 1,000 meters below the seabed. Statoil finds this economically preferable to paying the $55-per-ton tax that would apply if the carbon dioxide were simply vented. Thus, there is already proof of concept, even though a number of issues (e.g., environmental impacts, technological and economic feasibility, liability) remain to be resolved regarding each potential technological option. When combined with an economic structure where end-user energy needs in transportation and buildings are met through the use of hydrogen technologies, such carbon sequestration raises the possibility of being able to exploit fossil fuel reserves without substantial increases in carbon dioxide emissions.

An ESE approach would push further, though, and suggest that carbon sequestration, in combination with hydrogen end-use technologies, could become an important control mechanism in a deliberately engineered human carbon cycle governance system (Figure 1). Here, the global set of fossil fuel plants is tuned to produce over time the desired atmospheric concentration of carbon dioxide, given other variables (e.g., impacts on vegetation, desired degree of global climate change, lag times of various components of the systems involved, changes in solar insulation, other carbon

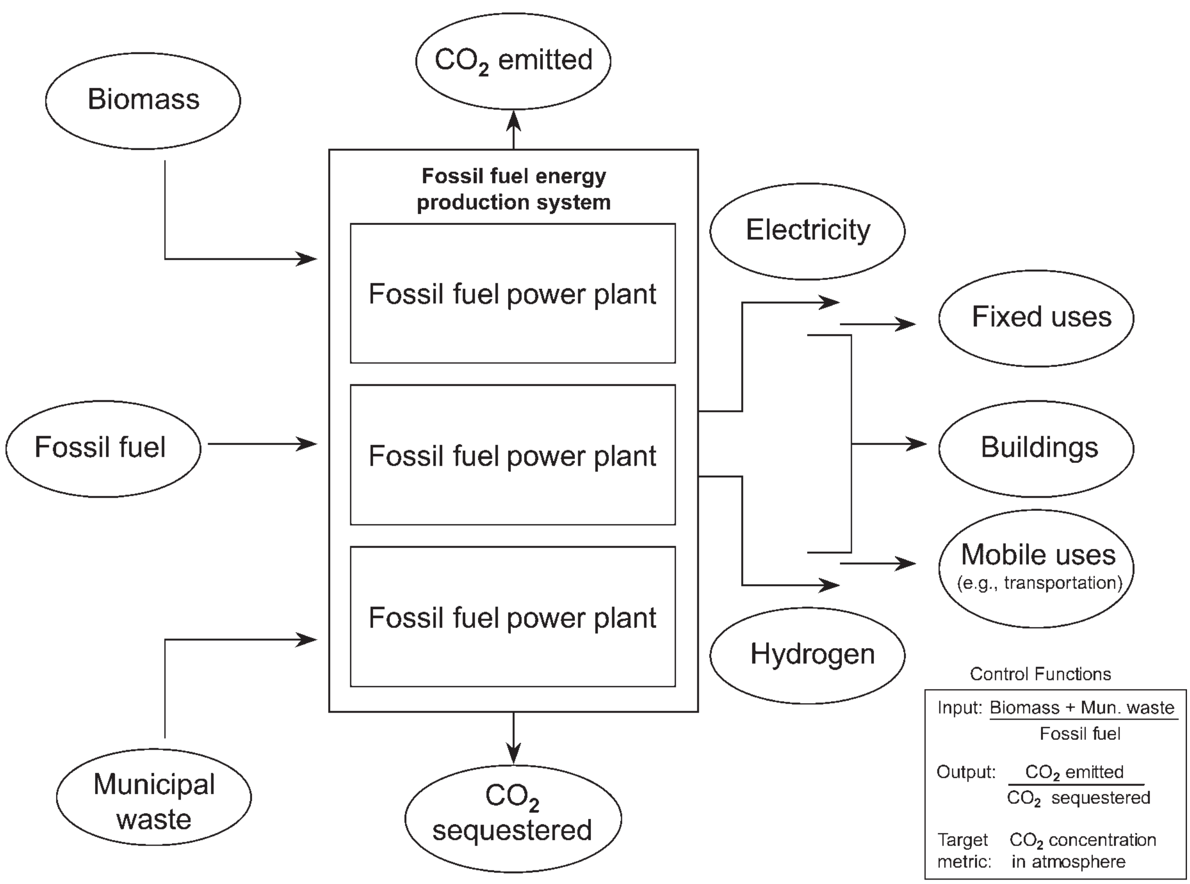

FIGURE 1 Carbon cycle governance system: fossil fuel power plant component.
SOURCE: B. R. Allenby, 1999a.

dioxide emissions, concentrations of other greenhouse gases, and the use of other mitigation technologies such as energy efficiency and biomass sequestration).

The control functions of such a system at the facility level are two-fold: the ratio of biomass and municipal waste to fossil fuel input into the system, and the amount of carbon dioxide emitted to that sequestered. At the systems level, the goal would be to move towards, and then maintain, a target atmospheric concentration. Of course, the fossil fuel plant control system would be combined with the entire suite of carbon control methods to accomplish this (Figure 2), and it must not be thought that each component would by any means be as susceptible to engineering control as the fossil fuel plant component. In fact, the system viewed as a whole has critical dynamics scaling over many magnitudes of temporal and spatial systems, with a daunting static and dynamic complexity. Indeed, many components of the carbon cycle system are not susceptible to direct management at all.

Ethical Considerations

ESE requires that human institutions not only accept moral responsibility for human-natural systems, but move beyond to assume an active management role for most global systems. Consider, for example, the approach adopted in the Kyoto negotiations, which relies on reducing global emissions of anthropogenic carbon dioxide and other greenhouse gas emissions to “safe” levels. This is a belated recognition of the ethical responsibility of humans for their effects on global climate, and, given the pervasive interpenetration of human and natural systems, is entirely inadequate from an engineering and management perspective. Accordingly, an ESE approach would require development of an institutional ability to deliberately modulate the carbon cycle within specified and desirable domains. One of these domains could well involve the maintenance of specified atmospheric concentrations of carbon dioxide and other greenhouse gases. However, it would not be thought of in isolation from other elements of the carbon cycle and coupled

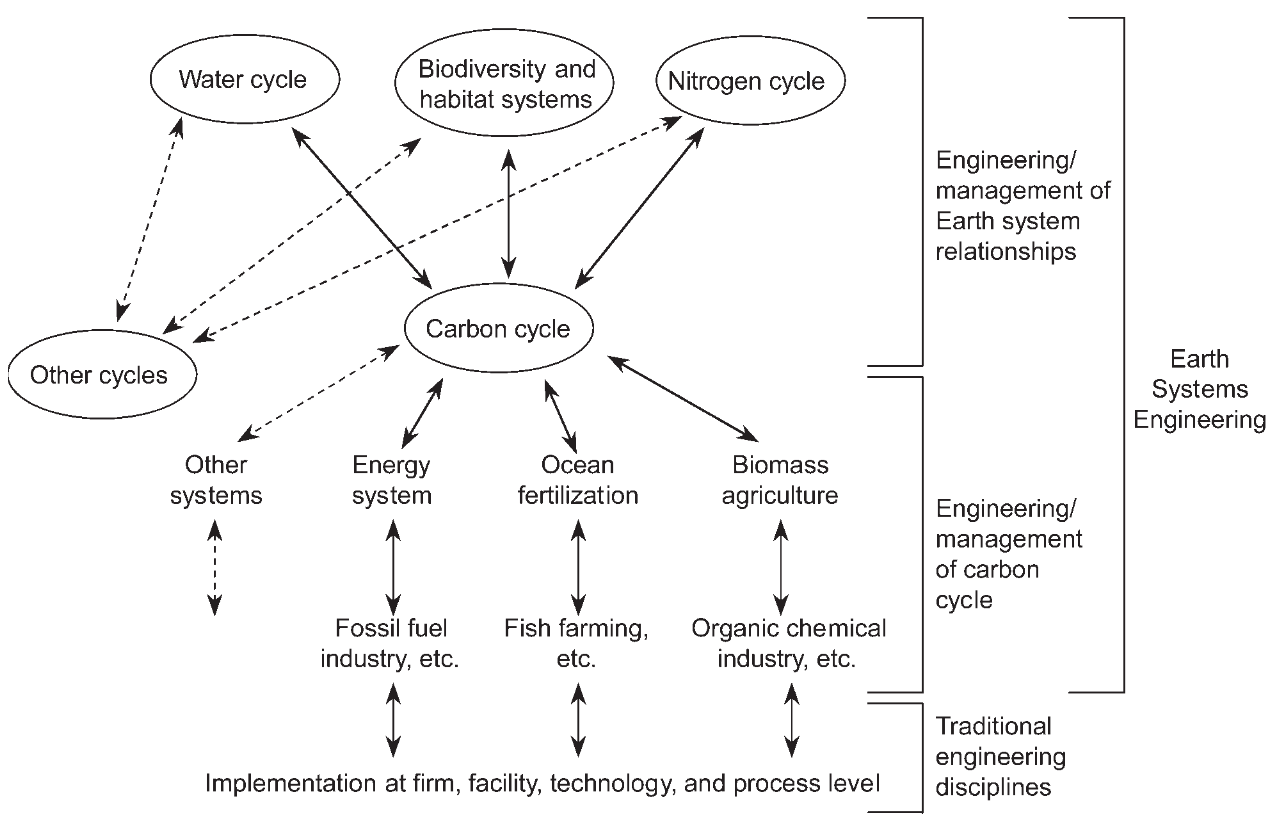

FIGURE 2 Carbon cycle: Earth systems engineering schematic.
SOURCE: B. R. Allenby, 1999a.

systems, nor would responses be focused on end-of-pipe emissions controls as they are now; rather, a suite of potential levers to affect systems change would be developed (Keith and Dowlatabadi, 1992).

This raises a fundamental issue: there is an ethical dimension to any consideration of Earth systems engineering, and that is the definition of desired endpoints. ESE is a means to an end which can only be defined in ethical terms. Simply put, the question "To what end are humans engineering, or should humans engineer, the Earth?" is a moral matter, not a technical one. Moreover, as with ESE itself, it is not hypothetical: human institutions are implicitly answering that question every day, and thus positing an answer. To date, however, failure to recognize the strong coupling between human activity and the state of environmental systems has permitted the engineering process to proceed without explicit consideration of the ethical content of the results. At some point this veil of ignorance will be pierced, perhaps in addressing the complex issues raised by global climate change and possible mitigation. But this has not occurred yet.

Failure to be sensitive to the ethical dimensions of ESE projects is, quite simply, bad engineering.

Some might argue that the idea of sustainable development—"development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987)—establishes that ethical framework, but it may be more likely that it has had the effect of lulling people into a false complacency. There are, in fact, a myriad of potential "sustainable" worlds, depending on the choices made regarding a number of dimensions of global civilization—that is, choices of a world sustainable with how many individuals, at what level of material well-being, with what level of equity, with what institutional systems, with what variability or stability, for how long, embodying what values (Cohen 1995). In fact, a cynic might argue that a more likely "sustainable world," given human history, is one characterized by economic and political elites protected from environmental and aesthetic insult by wealth and military power, with the political, economic, and cultural sustainability of such a structure maintained by high mortality rates among the poor and low levels of biodiversity.

We must recognize that a significant barrier to any substantial implementation of ESE is the lack of an adequately sophisticated ethical framework. In its absence, social acceptance of ESE and the institutional power it assumes is likely to be minimal, and justifiably so, until the necessary ethical competencies are developed. Unfortunately, it is not apparent where leadership in this dimension will come from, as there are currently no institutions which society has empowered to respond to this difficult challenge. This does not mean that individual ESE projects cannot go forward, particularly where they can be done in line with the guiding principles discussed below, and the perturbation to be addressed is immediate, difficult to reverse, and extensive in time and space. This does mean that the evolution of appropriate ethical and institutional structures is desirable, and should be actively encouraged by those who become interested in ESE. In this instance, failure to be sensitive to the ethical dimensions of ESE projects is, quite simply, bad engineering.

Principles of Earth Systems Engineering

Even given the nascent state of ESE, and the lack of supporting institutional and ethical frameworks, it is possible to generate some preliminary principles that should govern ESE. In doing so, for example, we can draw on previous experience with large engineering projects (especially hydrologic and civil) and complex technological systems such as the U.S. space shuttle program, global air transport control and safety programs, and nuclear power systems in many countries. Without pretending to comprehensiveness, then, here are some obvious ESE principles:

1. Only intervene when required, and to the extent required. The traditional medical axiom, "first, do no harm," is a reflection of humility in the face of complexity which is equally appropriate for Earth systems engineering. In this sense, ESE more reflects a medical diagnosis model than a traditional engineering model.

2. Know what the objectives of any intervention are from the beginning, and establish metrics which can *(a)*

track progress towards satisfying the objectives and *(b)* provide early warning of unanticipated or problematic system responses. Requiring such preparation for ESE activities is useful not just in itself, but because it implicitly requires that the boundaries of the systems involved be defined, and at least a hypothesized model of systems behavior be developed.

3. Engineering such systems must not be based on implicit or explicit models of centralized control in the traditional rigid sense. Such an approach is appropriate for simple, well-known systems, but not for the complex, unpredictable, and contingent systems involved here. In many cases, these projects will require integrated management of coupled biological, physical, and traditional engineered systems with high levels of uncertainty, and control and feedback mechanisms will be widely distributed along many temporal and spatial scales (NASA has faced some of these issues in its attempts to build space colonies; see NASA, 1979). Rather than attempting to dominate a defined system, the Earth systems engineer will have to see herself or himself as an integral component of the system itself, closely coupled with its evolution and subject to many of its dynamics, with all the self-referential implications. This self-referential pattern is already evident in the global climate change arena, where human decisions about acceptable levels of global climate change forcing affect atmospheric concentrations of carbon dioxide, which in turn feed back into responsive engineering activities (like designing fossil fuel plants to sequester carbon). This will require an entirely different psychology of engineering.

4. Whenever possible, engineered changes should be incremental and reversible, rather than fundamental and irreversible. There must be room for the continuous learning and feedback that incremental engineering interventions support. In all cases, scale-up should allow for the fact that, especially in complex systems, discontinuities and emergent characteristics are the rule, not the exception, as scales change.

5. In a similar vein, experience with existing systems engineering projects demonstrates that the focus of the Earth systems engineer will be on the characteristics and dynamics of the system *qua* system—the interfaces, links, and feedback loops among systems components—rather than just on the constituent artifacts. The focus is on system state, rather than on artifact construction.

6. Continual learning at the personal and institutional level must be built into the process, as is the case now in "high reliability organizations," or HROs, such as aircraft carrier operations or well-run nuclear power plants (Pool, 1997). This learning process is messy and highly multidisciplinary, and accordingly difficult to maintain even in the best of circumstances. It is also problematic because the learning will probably have to occur at an institutional rather than personal level because of the complexity of the systems involved and the inability of any single person, no matter how qualified, to understand them in their entirety.

7. ESE must explicitly accept high levels of uncertainty as endogenous to the engineering function, rather than thinking of engineering as an effort to create a system certain. The mental model must be one of working within complex systems where uncertainty and variability are endemic, not simple systems where it is possible to define system outputs from known inputs unambiguously (Allenby, 1999b). For example, as Morgan and Dowlatabadi (1997) point out, "nonlinear processes that determine climate span roughly 12 orders of magnitude, from microscopic to planetary scales, and it is doubtful whether even future supercomputers will be able to model processes across as much as half that range." These are the types of systems with which Earth systems engineering will have to deal.

ESE must explicitly accept high levels of uncertainty as endogenous to the engineering function.

8. Similarly, because of the complexity of Earth systems engineering projects, management and organizational skills will be as important to success as traditional engineering skills. Stakeholder management, transparent processes for defining and implementing

projects, and managing to social and cultural objectives (as well as scientific and technological ones) will be necessary.

9. An important goal in Earth systems engineering projects should be to support the evolution of resiliency, not just redundancy, in the system. The two are different: a redundant system may have a backup mechanism for a particular subsystem, yet still be subject to difficult-to-predict catastrophic failure; a resilient system will resist degradation and, when necessary, will degrade gracefully, even under unanticipated assaults.

The question is not whether humans are engineering Earth systems, but whether humans will do so rationally, intelligently, and ethically.

Thus, for example, a resilient strategy for global climate change and carbon cycle management would include not just carbon cycle management utilizing a variety of mechanisms (e.g., iron fertilization, carbon sequestration, reforestation), but a broader range of mitigation options as well (Rubin et al., 1992). Should any single option fail or prove to be too expensive, the engineering and management program could adjust gracefully elsewhere using other mechanisms (e.g., energy efficiency and demand side management). That is, even though each engineered option might be subject to failure, the system itself would be engineered and managed to be resilient.

10. Analogously, it is preferable to design (or encourage the evolution of) inherently safe systems, rather than engineered safe systems. An inherently safe system, when it fails, fails in a noncatastrophic way. An engineered safe system is designed to reduce the risk of catastrophic failure, but there is still a finite probability that such a failure may occur. Light-water nuclear power plants, for example, are engineered to be safe, but, as Three Mile Island demonstrated, are not *inherently* safe. Thus, for example, if one were concerned about the possible failure of underground carbon dioxide sinks and the potential release of substantial amounts of the gas in a lethal manner, one would preferentially use deep geologic aquifers under the ocean, rather than under populated areas. If the former failed, the carbon dioxide would (most probably) be contained in the deep ocean; if the latter failed, the escaping gas might impact human populations.

11. There must be adequate resources available to support both the project and the science and technology research and development which will be necessary to ensure that the responses of the relevant systems are understood. Financial pressures can be particularly insidious with complex engineering technologies even today (Pool [1997] cites the Bhopal Union Carbide chemical plant and the Challenger incident as examples where pressures generated in part as a result of chronic underfunding resulted in catastrophic failure of such systems). Earth systems engineering projects are likely to be at least as complex as existing technological systems, and to last over longer time periods than the usual budgetary cycles, meaning that they may be particularly prone to financial fluctuations.

12. If any Earth systems engineering project is to achieve public acceptance and social legitimacy, it must at all stages be characterized by an inclusive dialogue among all stakeholders. Not all of them will agree, for a number of reasons, but to be successful, a project requires broad public support. The most obvious example of a complex technology system where these mechanisms have proven inadequate is, of course, civilian nuclear power. In the United States, for example, the secrecy and technological hubris which grew out of the nuclear weapons program and the nuclear Navy meant that both the regulators and the experts were culturally adverse to open communication and dialogue, with eventual results for the industry that were both predictable and disastrous (Pool, 1997).

Conclusion

Earth systems engineering may be defined as the study and practice of engineering human technology systems and related elements of natural systems in such a way as to provide the required functionality while facilitating the active management of the dynamics of, and minimizing the risk and scale of unplanned or undesirable perturbations in, strongly coupled fundamental natural systems. ESE involves developing technologies and strategies for managing complex coupled human-natural systems at very different scales, from highly granular to broadly integrated, in a comprehensive manner. This new area of engineering can draw on significant experience from past practices and results, particularly derived from projects involving complex technology systems or large natural systems (e.g., irrigation), and can draw much support from the evolving field of industrial ecology. Even so, it is apparent that the science and technology and the institutional and ethical infrastructures to support such approaches do not yet exist, although progress in relevant disciplines and technologies has been made on a piecemeal basis. This, and the fact that unanticipated consequences of such major programs could be quite significant, argues for a cautious and balanced effort to begin such a program. Fundamentally, however, the question is not whether humans are engineering Earth systems, but whether humans will do so rationally, intelligently, and ethically.

Notes

1. The opinions expressed in this paper are those of the author only, and do not necessarily represent those of AT&T, Columbia University, or any other entity with which the author has been or is now affiliated.

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The Engineered Century

Neil A. Armstrong

A century hence, 2000 may be viewed as quite a primitive period in human history. It's something to hope for.

Neil Armstrong, NAE, is a former astronaut and chairman of AIL Technologies. This article is an edited version of his remarks delivered at the National Press Club, 22 February 2000.

Fellow engineers, honored guests, ladies and gentlemen: It is National Engineers Week, and I am honored to be speaking on behalf of the National Academy of Engineering and our nation's professional engineering societies.

I am, and ever will be, a white-socks, pocket-protector, nerdy engineer—born under the second law of thermodynamics, steeped in the steam tables, in love with free-body diagrams, transformed by Laplace, and propelled by compressible flow.

As an engineer, I take a substantial amount of pride in the accomplishments of my profession. Bill Wulf, president of the National Academy of Engineering, has said that science is about what *is,* and engineering is about what *can be.* The Greek letter eta, in lower case, often shows up in engineering documents. Engineers pay a good bit of attention to improving eta because it is a symbol for efficiency—doing an equivalent or better job with less weight, less power, less time, less cost. The entire existence of engineers is dedicated to doing things better and more efficiently.

When knowledge, facts, or solutions are sought, there are a number of techniques available from which to select. These techniques can be ranked according to their effectiveness, from the most certain to the most uncertain. At the top, or level one, is measurement; but even excellent measurements can be subject to small amounts of error. Level two is cause and effect. That's a rigorous deduction based on the laws of nature; on the conservation of mass, energy, and momentum; on Newtonian mechanics, Ohm's law, Charles's law, and all those kinds of relationships. These techniques for solving problems are not error free, but they do provide reliable and repeatable results.

At the third level I put correlation studies. These are statistical techniques which allow the drawing of general and reasonable conclusions, but imprecise conclusions. An example of this is when you hear a conclusion such as 62 percent of the people who eat pistachio ice cream 20 or more times a week tend to gain weight.

The fourth level is opinion sampling. Conclusions here can be useful, but they are often temperable and not repeatable. Levels five, six, seven, and eight include a variety of techniques that vary from focus groups to intuition to dream analysis and just plain guessing.

Uncertainty increases with the number of independent variables. So engineers use measurement and cause-and-effect methods for problem solving as much as possible, and use correlation studies only when the number of independent variables is too great for explicit solutions.

Engineering and the Quality of Life

Engineering is a profession which leaves its imprint on our society in countless ways. We all intuitively understand the term "quality of life," but we have difficulty in attempting to define it. Each individual has a unique group of factors which are important to him or her in quality of life. One person might think having no obligation to work whatsoever would be ideal, while another person would think having a great deal of work to do would be ideal. We do know that a century ago the world really needed improvements in quality of life—health, mobility, living standards. At that time, life was a constant struggle. There were epidemics of tuberculosis. Child labor and 12-hour work days were used to ensure economic output. The average life expectancy had barely budged in a thousand years. If you reached senior-citizen status you beat the odds; to have all your children reach adulthood was rare. Waterborne diseases like typhoid fever and cholera were scourges around the globe. Industries blanketed cities with soot. Streets were filled with garbage and sewage. The world's forests were being decimated to fuel burgeoning industries and to build and heat homes for the world's growing population.

The twentieth century was often punctuated with the terror of war and darkened with societal struggles to overcome injustice. But it was also the first century in which technology enabled the tenets and the images of those traumas to reach across the world and touch people in ways that were previously unimagined. John Pierce, the engineer who fathered Telstar, the first satellite to relay television signals across the Atlantic, said that engineering helped create a world in which no injustice could be hidden.

I am, and ever will be, a white-socks, pocket-protector, nerdy engineer.

Engineers are dedicated to solving problems and creating new, useful, and efficient things. So should not the world admire and respect them? Answer: Only occasionally.

Many of our fellow citizens are mistrustful of logic and critical of technocrats, and often with reason. Bridges fail, airplanes crash, storage tanks leak, radiation escapes, and automobiles are recalled. Such failures are reported widely, and the search for whom to blame is initiated. But there are a couple of problems here. Engineers are not good communicators. We are mistrusted because we are perceived as being slaves to technology, as technocrats who don't care a whit about the environment or safety or human values. And I reject those criticisms. In my experience, engineers aren't really bad folks. A little too focused, maybe too intense for some, but they are as caring and concerned as other segments of our society. The fact that their failures are so widely reported is evidence of their rarity.

Now, in this final year of the twentieth century, many will look back to see how we have changed and what we have accomplished. By measuring our successes and our failures, they will gauge the progress that we have made as individuals and as a society. The evolution of popular culture, politics, and business has given us a world that is vastly different from that of our grandparents, and engineering has played a significant role in those changes. So we decided we would take a focused look at how engineering has affected the quality of life in this past century.

Engineering is a profession which leaves its imprint on our society in countless ways.

Over the past year, a rather impressive consortium of professional engineering societies, representing nearly every engineering discipline, has given its time, resources, and attention to a nationwide effort to identify and communicate the ways that engineering has affected our lives. Engineering is the second largest profession in the United States, behind teaching, and so a large group of minds was looking at this issue.

Each organization independently polled its membership to find out what individual engineers believed to be the greatest achievements in their respective fields. This effort covered areas as diverse as agricultural engineering, chemical engineering, electrical and mechanical engineering, aerospace engineering, and so on. Because these professional societies are unrelated to each other, the American Association of Engineering Societies and the National Academy of Engineering (NAE) provided the groundwork to coordinate the effort. The Academy, in particular, took a leadership role in this effort because of its unique ability to convene the world's greatest engineering minds under the congressional charter that it shares with the National Academy of Sciences.

The NAE issued the call for nominations to the societies, convened a selection committee of top engineers from all fields, and set about the laborious practice of qualifying and quantifying the information in the nominations. I was pleased to be asked to serve on the selection committee, which was chaired so capably by Guy Stever.

After several rounds of narrowing the nominations, the committee met for two full days toward the end of last year and debated about just how to tackle this task and determine which engineering achievements of the twentieth century had the greatest positive effect on humankind. While intercontinental ballistic missiles and laser-guided bombs were undoubtedly technological marvels with important and perhaps justifiable reasons for their existence, projects of this type were somewhat disadvantaged on the quality-of-life basis.

Engineers should, and often do, present their projects, their ideas, and their conclusions with both the strengths and the weaknesses in full view. And I feel an obligation to maintain that tradition. A popular 14th century phrase was "comparisons are odious," and perhaps they are. Nevertheless, we are, in contemporary society, engulfed in comparisons and ratings and lists: the top 25 teams, the top 10 money winners, the Oscars, the Emmys, the Grammys, the bestsellers, etc. And we engineers, not to be left out, have developed our own list.

Such lists are, admittedly, somewhat self-serving. This one certainly is. In making comparisons among engineering achievements, we could not use measurements, and we found it difficult to use cause-and-effect or correlation studies. So we were obliged to reach way down to level four, opinion sampling, to reach consensus. Although this was an uncomfortable process for engineers, the NAE did aggregate a committee of exceptional breadth and experience, considered seriously the recommendations of the nominators—all well-informed and experienced engineers in their respective fields—and sifted (see story on page 34).

The Greatest Engineering Achievements of the 20th Century

Now, as we take a look at the things considered by the NAE, we will see that if any of them were removed, our world would be a very different and less hospitable place. Each one of these achievements has been important to the change in our society.

If you were to ask a person on the street to name a great engineering achievement, he or she might say the Golden Gate Bridge, or the Panama Canal, or the Empire State Building. And while each of those is a great engineering achievement, none of them made the list. What did make the list were technologies that have become inextricable parts of the fabric of our lives—some spectacular, some nearly invisible, but all critically important. So, let me introduce you to the list, the 20 engineering achievements that had the greatest positive impact on society in the twentieth century.

At number 20 we have high-performance materials. Early in the century the first synthetic resins were developed, and plastics have since become ubiquitous worldwide. In the second half of the century, polymers, composites, and ceramic materials found extensive applications.

Number 19 is nuclear technology. Although controversial in the public mind, the engineering achievements related to conflict deterrence, power generation, and medical diagnostics and treatment remain among the most important of the twentieth century.

At number 18 are lasers and fiber optics. Lasers brought xerographic printers and bar code readers, transformed survey methods, and revolutionized the storage of music, data, and images. And when the laser was combined with optical fiber, the rate of information flow was dramatically increased. Tonight, three engineers who were key players in the development of optical fiber will receive the NAE's Charles Stark Draper Prize (see story on page 40).

Number 17 is petroleum and petrochemical technologies. Transportation became petroleum-based in the twentieth century, as did much of the energy and chemical industries. Next, at 16, are health technologies, which include devices such as pacemakers, artificial limbs, eye lens implants, and so on.

At fifteen are household appliances, which radically reduced the drudgery and time required to maintain a home. At number 14 are imaging technologies, like those used for medical diagnostics and weather forecasting. Next is the Internet, which to the surprise of many made it only to number 13. It was the consensus of the committee that the impact of the Internet will be felt more significantly in the twenty-first century. Check later.

I believe that space flight was certainly one of, and perhaps *the* greatest engineering achievement of the century, but it was selected number 12 on the basis of its effect on the quality of life, and I do not disagree. While the impact of seeing our planet from afar had an overpowering effect on people around the Earth and provided the technology for tens of thousands of new products, other nominees were judged to have a greater impact on worldwide living standards.

Next is the interstate highway system. With 44,000 miles of limited-access, multiple-lane roads without a single stop sign or stop light, it's a model of efficiency and an engineer's dream. While it clearly improves the lives of all who travel on it and all who are served by it, its rating suffers because it is not worldwide.

Moving on to the top 10, we have air conditioning and refrigeration, which provided improvements in comfort and health and gave us the ability to transport fresh food and extend its shelf life.

Next is the telephone. Instantaneous worldwide communications serve both family and business needs, and have introduced telemarketing to the dinner hour.

When the founder of IBM, Tom Watson, reportedly predicted before World War II that there was a world market for about 5 computers, he slightly underestimated the number of machines and applications for these devices, which reached number 8 on our list.

The world's population grew from 1.6 billion to 6 billion souls during this past century, a milestone that could not have been reached without number 7, agricultural mechanization. More impressive is the fact that the portion of the population necessary to feed the world has been reduced from slightly more than half in 1900 to just a few percent today.

Seeing our planet from afar had an overpowering effect on people around the Earth.

One step higher, at number 6, are radio and television. Although Marconi first demonstrated radio in 1895, he broadcast the first transoceanic signal in 1901, sufficient justification for the committee to include radio on the list. Some countries first introduced television to enable their citizenry to watch the Apollo achievements as they happened. And now it's difficult to find a place on the entire globe that is not burdened with daytime television.

In the fifth position is electronics, from vacuum tubes to transistors, integrated circuits, and microcircuitry. I'm told that in midcentury the transistorized radio was the fastest-selling retail item of all time—at least up until the time of Pokémon.

Fourth are the technologies that purify and deliver safe and abundant water. At the outset of the century in the United States, typhoid alone killed more than 150 of each 100,000 citizens. Water treatment and distribution techniques led to longer lives and better living standards around the globe.

The airplane is ranked third. From its birth in 1903 with no obvious important use, aircraft rapidly changed the character of warfare, found dozens of new uses, and in the latter half of the century decimated passenger competition in trains and ships.

The second ranked engineering contribution is the automobile. It too was a nineteenth century invention, but its development in the twentieth century demanded that it be considered a competitor. Passenger cars and trucks are the major transporter of people and cargo around the world, and the automobile has expanded the ease, practicality, and affordability of short- to medium-range travel enormously.

Truly, it has been a magical century.

Now, at this point, if we were in the entertainment world, we would have drum rolls, fanfares, and rockets. But as engineers we are not so inclined—well, maybe a few rockets. The winner, the top-rated engineering improvement to the life of earthlings in this century was electrification.

The majority of the top 20 achievements would not have been possible without electricity. Electrification changed the country's economic development and gave rural populations the same opportunities and amenities as people in the cities. It provides the power for small appliances in the home, for computers in control rooms that route power and telecommunications, and for the machinery that produces capital goods and consumer products. If anything shines as an example of how engineering has changed the world during the twentieth century, it is clearly the power that we use in our homes and businesses.

So, there you have it, the top 20. My descriptions have been sometimes trite, and it's likely that I missed some of the most important societal contributions from the nominees. And, without question, I did not even mention the work from those nominations that did not make the top 20 list, yet in many cases were of enormous importance to certain sectors of society or certain parts of the world. And in all honestly, I am guilty of a bit of subterfuge. Certainly the nominations were worthy and the committee was honest and diligent in evaluating them. And certainly you have been given their well-reasoned conclusions. The subterfuge is that my purpose was not to promote the competitive nature of the event, or to congratulate the winner, or to convince you that electrification was the most important technical activity of this past century. All of you have your own opinions on the importance of various technical developments to our society. What I really hoped to do was shamelessly use this occasion to remind you of the breadth, and the depth, and the importance of engineering as a whole to human existence, human progress, and human happiness.

There are perhaps, even more far-reaching consequences of this exercise. The likelihood of today marking the end of creative engineering is nil. The future is a bit foggy, but it's not unreasonable to suggest that the twenty-first century will enjoy a rate of progress not unlike the twentieth. And a century hence, 2000 may be viewed as quite a primitive period in human history. It's something to hope for.

For three decades I have enjoyed the work and friendship of Arthur Clarke, a prolific science and science fiction writer, who back in 1945 first suggested the possibility of the communications satellite. In addition to writing some wonderful books, he has also proposed a few memorable laws. Clarke's third law seems particularly apt today: Any sufficiently developed technology is indistinguishable from magic.

Truly, it has been a magical century.

Functional Biomedical Imaging

Thomas F. Budinger

New engineering will enable diagnosis and advance treatment of the major health problems.

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This article focuses on the engineering facets that are key to the development of the human imaging technologies of X-ray computed tomography (X-ray CT), magnetic resonance imaging (MRI), positron emission tomography (PET), and single photon emission computed tomography (SPECT). These technologies were selected to demonstrate future plausible developments through the use of examples of imaging brain function, heart function, arthritis, vertebral disc disease, prostate cancer, breast cancer, and colorectal tumors. Ultrasound and other imaging methods not included herein are discussed in *Mathematics and Physics of Emerging Biomedical Imaging,* a publication by a National Research Council panel on mathematics and physics in emerging biomedical imaging techniques (Budinger et al., 1996a).

PET gives images of the distribution of an injected positron-emitting radionuclide usually attached to a compound such as an analogue of sugar. The radiation dose is usually less than the dose that individuals receive from natural background each year. These radionuclides have short half-lives (e.g., 2 to 109 minutes) and are produced in cyclotrons or reactors. When the positron emitter (e.g., carbon-11, oxygen-15, nitrogen-13, or fluorine-18) decays, the positron (a positive electron) interacts with a local electron and the masses of the positron and electron are converted to two high-energy photons that travel in opposite directions and are detected by a scintillation crystal and a photoelectron multiplier tube. The detector material and electronics are key elements for the present and future development of this technique.

At present, the detector is a scintillator that converts the high-energy photon into light, which is converted to an electric current by the photoelectron multiplier tube. Small arrays of detectors with newly invented scintillators sandwiched between a photodiode array and an array of photoelectron multiplier tubes have now been developed that can achieve spatial resolution of 2 mm for brain imaging. It has taken 22 years to reduce the dark current from 200 nanoamperes to 20 picoamperes for low-noise photodiode arrays (Budinger et al., 1996b). In the future, avalanche detector systems may replace photoelectron multiplier tubes, allowing construction of very compact systems.

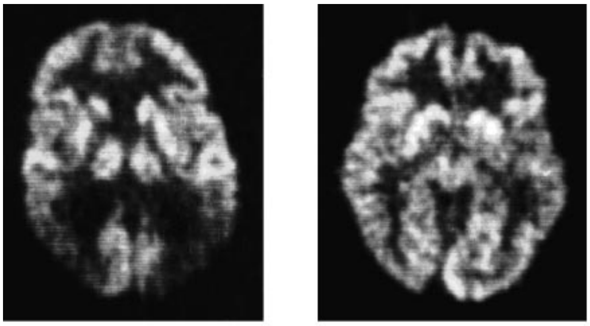

FIGURE 1 PET of the spatial distribution of fluoride-18 deoxyglucose representing glucose metabolism in the brain.

The major attribute of PET and SPECT that distinguishes them from MRI and X-ray CT methods is the high sensitivity with which they can detect metabolic activity and trace the concentration of specific proteins in the body (e.g., neuroreceptor proteins of the brain) (Budinger, 1995; Cherry and Phelps, 1995). PET scans detect tracers in the nanomolar concentration range, allowing studies of diseases such as schizophrenia, manic depressive diseases, and Alzheimer's disease.

An example of the image of glucose metabolism reflected by the accumulation of fluoride-18 deoxyglucose, an analogue of glucose, is shown in Figure 1. In the brains of people with Alzheimer's disease, there is a decrease in metabolism in the parietal regions of the cerebral cortex. This is one of the regions of the brain that processes memory. Understanding the neural chemistry that leads to this decrease in glucose metabolism requires a detector system with much higher resolution than exists today, because the areas that control this region are deep in the brain and in the range of 2 mm in size.

TABLE 1 Improvements in PET resolution.

Year	Resolution
1974	17.0 mm
1978	9.0 mm
1982	7.0 mm
1987	3.0 mm
1992	2.6 mm
2004	> 2.0 mm

Another example of the specificity of the PET technique is the definition of the dopamine system, which is the neural component of the brain affected by Parkinson's disease. Resolution improved from 17 mm in the mid-1970s to 2.6 mm in the mid-1990s (Table 1), and further improvements can be expected in the near future. Current levels of resolution will enable studies of abnormal brain chemistry in diseases such as manic depressive disorders, schizophrenia, and other mental disorders.

Magnetic Resonance Imaging

The three categories of magnetic resonance now being used are magnetic resonance proton imaging, magnetic resonance spectroscopy (MRS), and functional MRI (fMRI) (Chen and Ugurbil, 1999). The magnetic resonance image is an image of the distribution of hydrogen nuclei associated with water (Figure 2). The contrast between gray and white matter in these images is due to the rate of signal decay, which is dependent on the local tissue environment. MRS has the unique capability to detect the chemical composition of tissues, but the method requires concentrations of substances to be in the millimolar range. By contrast, emission techniques (e.g., PET) can detect tracers a million times less concentrated than general magnetic resonance. New engineering leading to higher-resolution fields will result in improved MRS sensitivity. In 1986, Paul Lauterbur and the author started the effort to create a national resource whole-body magnet at 10 teslas (T) that would allow studies of compounds having less than 1 millimolar concentrations. The need for high-resolution fields for brain studies are discussed below.

Functional Brain Imaging

Three types of dynamic brain function are quantifiable by noninvasive imaging: blood flow changes in response to sensory or mental activity, neurochemical activity, and metabolic activity of energy consumption (e.g., glucose and oxygen consumption). Radiotracer techniques have shown that blood flow in the capillary bed of small regions of the brain increases 2 to 30 percent when that region is called on to increase nerve activity by some external or internal stimulus. The more recent advent of MRI methods for detecting a signal change associated with this local activity makes it possible to measure mental functioning noninvasively without the use of radiation. Thus, there has been a surge of activity in the area of fMRI.

PET and fMRI were compared for their ability to detect activation of the area of the brain important for processing noxious images or odors (Irwin et al., 1996; Zald and Pardo, 1997). Immediately after the stimulus arrived in the appropriate cerebral cortex area, PET showed flow or volume by the rate of accumulation of a flow tracer. MRI showed a signal that reflects the change in the local magnetic environment because of a difference in the amounts of oxy- and deoxyhemoglobin in that area. Oxyhemoglobin is diamagnetic and deoxyhemoglobin is paramagnetic. The concentrations of oxyhemoglobin and deoxyhemoglobin in local regions change, and these changes are visualized by subtracting the image after activation from the image before activation. Activation of neurons is followed by an increase in neuron metabolism.

The results of the fMRI method are expressed in terms of the so-called BOLD (blood oxygen level dependent) effect. A momentary decline in oxyhemoglobin of 0.5 percent negative BOLD effect was seen recently at 4 T; blood flow then increased to compensate for the loss of local oxygen. The positive BOLD signal is the result of an overflow, and the signal seen in most studies at 1.5 T is not from the precise area activated, but is rather from the arterial and venous blood draining the activated region. This functional activation can be confusing to the neuroscientist who wants to know exactly which nerve cells are being activated, and the need of better signal-to-noise ratio has led investigators to use stronger and stronger magnetic fields. Using 4-T rather than 1.5-T fields clearly showed that there is an initial drop in signal followed by a reactive flooding of the area with blood, resulting in more oxyhemoglobin being delivered than is needed to sustain or keep ahead of the neuronal metabolic demands.

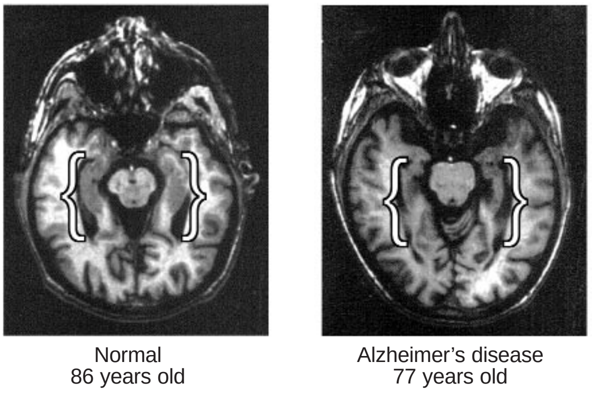

FIGURE 2 MRI of a transaxial plane through the brain showing atrophy of the hippocampal areas (highlighted in brackets) in Alzheimer's disease.

From a clinical standpoint, fMRI has applications in identifying areas of the brain to be avoided in surgery (e.g., for tumor excision). The scientific future of the technology depends in good part on an improved signal-to-noise ratio. The noise artifacts from heart, respiratory, and patient motion accompanying the activation procedure and other effects are amplified by the after-minus-before subtraction method. This amplification, along with a low signal-to-noise ratio, often results in a need for repeated studies. The electrical engineering methods of signal processing have been successful in retrieving the true signal, but even at 4 T the signal change is only 3 percent, whereas flow changes of 30 percent are quantitatively measured using radioactive methods. Thus, to achieve reliable scientific data when exploring brain function, fields of 4 T and higher are required. Two recent installations at 7 T (University of Minnesota) and 8 T (Ohio State University) will allow studies of brain function beyond sensory and motor function (e.g., mental activity).

The evolution of high-field human MRI from 1.5 T to 8 T or above will enable detection of metabolites by using carbon-13 patterns associated with specific compounds and detection of electrolytes such as potassium and sodium. It is even possible to evaluate the proportion of intra- and extracellular concentration of these ions with quadripolar moments by using multiple quantum methods associated with imaging (Lack et al., 1995; Schepkin et al., 1996; Star-Lack et al., 1997). These methods will allow studies of the mechanisms of diseases such as manic depressive disorders.

Neurochemistry of the brain can also be studied noninvasively by using radioactive techniques such as imaging ligands which depict the activity of the dopaminergic neurons whose abnormal functioning is known in Parkinson's disease and is suspected in schizophrenia and other mental diseases.

Coronary artery disease remains a major cause of early death.

Deaths from coronary atherosclerosis have declined dramatically in the past 20 years. An estimated 1 million lives per year are saved due to a lower incidence of certain risk factors (e.g., smoking and high-fat diet) and by medical interventions (e.g., lipoprotein-modifying medication, antihypertensive drugs, beta blockers, and surgery). Nevertheless, coronary artery disease remains a major cause of early death and a major health-cost factor.

The contemporary methods of evaluating coronary arteries involve X-ray imaging of the coronary arteries after injection of contrast material via catheterization. Catheterization is expensive and has some medical risks and thus is not used as a routine screening method for the detection of atherosclerosis. The early and inexpensive diagnosis of coronary artery disease through advanced computed tomography methods and cardiac MRI is possible in the near future, but only through engineering innovations.

X-ray CT technology recently achieved an important role in detecting coronary artery disease by a noninvasive technique that is able to demonstrate calcium deposits in diseased coronary artery walls. Using electron-beam technology where the beam instead of the gantry is moved back and forth over the cathode allows one to collect data rapidly to avoid the motion artifact of the beating heart. This new type of study is rapid, inexpensive, and uses a low dose of radiation, and the results show pathology in the vessel wall rather than changes in lumen diameter, which can be less sensitive in 50 percent of patients with atherosclerosis but little or no constriction of the coronary vasculature.

MRI Heart Imaging

By using MRI, it is possible to show the flow channels in the heart without catheterization. Three recent developments show the near-term potential of this imaging technique. First, the existence of flowing blood allows the MRI procedure to emphasize differences between moving protons in blood and surrounding stationary tissue; thus, though the use of specialized pulse sequences, the major branches of the coronary arteries can be visualized. This visualization can be enhanced by using magnetic resonance contrast material such as natural albumin with an attached paramagnetic element (gadolinium), which is now in clinical trials. This material is injected intravenously and will stay in the lumen of vessels for a period sufficient to allow visualization of the vessels in the body by MRI methods. The material is now under review by the Food and Drug Administration.

The second enabling technology is the development of a very fast scanning method wherein the magnetic field gradients are switched very rapidly in order to gather image data that can be reconstituted to avoid motion distortion. The third enabling engineering technology is the development of MRI units that allow ease of access for both patient and attendants. Thus, in the near future, we can expect to have pictures of our coronary trees as part of our medical evaluation just as today we have records of the waveforms of electrical activity of the heart, such as the electrocardiogram, in our medical records.

Radionuclide methods of measuring blood flow to the heart muscle have played an essential role in the diagnosis of coronary artery disease. The isotope delivery to the muscle can be a more sensitive measure of flow than anatomy images. However, although diagnoses and modern medical therapies applied before or during the acute cardiac attack have reduced the death rate from coronary artery disease by 22 percent in the past 20 years, the incidence of hospital visits from patients with congestive heart failure (i.e., mechanical output deficit relative to the blood volume flow needed for everyday activities) has gone up by a factor of 4 in the same period of time for patients over 60. There are 400,000 new congestive heart failure cases every year. After the onset of this disease in women, the life span is 3 years; in men, it is 1.5 years. The prevalence is over 4 million. There is no cure for this problem except transplantation or artificial assist devices.

Treating Congestive Heart Failure

Congestive heart failure is caused not only by the stress on the heart muscle due to atherosclerosis, but by untreated hypertension, metabolic or viral diseases, and possibly responses to excessive mental stress. There is a progressive failure of the pumping ability of the heart that has undergone the stress of having part of the muscle sack rendered ineffective by a previous heart attack, or by the results of misrepair (remodeling errors) in response to chronic stress. As the good muscle pumps blood out through the aorta, it also puts pressure on the portion of the heart wall that is unable to contract as well as the good muscle. The stress at the interface between the good muscle and the weak muscle could lead to the same consequences as continued stress on the entire heart muscle from long-term untreated hypertension.

What might be going on in the heart muscle complex? The National Heart, Lung, and Blood Institute recognizes that congestive heart failure is now a major problem in health care, a problem that is very poorly understood and inadequately treated. An engineering approach to this disease promises to reveal both the mechanisms involved and the proper treatment. Although 70 percent of the heart muscle volume consists of muscle cells (myocytes), these cells are only 30 percent of the total cells in the heart. The remaining 70 percent of cells are associated with the blood vessels and the scaffolding that organizes myocytes, which must contract and relax in synchrony and in well-defined directions for efficient pumping.

Collagen, a protein that forms fibers with the tensile strength of Kevlar, is the major material of the scaffolding. Thus, the maintenance of the human heart during normal and stressful functioning operations must involve collagen maintenance. Surprisingly, the turnover time for collagen in the heart is one month, or 3 percent per day. Imagine the situation: constant remodeling of a bridge structure every month while the myocytes contract in synchrony. Congestive heart failure appears to be a problem of collagen scaffold remodeling, but this has not been conclusively demonstrated. After tissue stress (e.g., a twisted ankle or skin scratch) there is an invasion at the site of injury by fibroblasts, which endeavor to repair the injury. Very frequently, this repair effort causes further injury if not controlled by anti-inflammatory agents (Luster, 1998).

New developments in both PET and MRI can play a major role in the understanding and treatment of congestive heart failure. PET can measure the activity of collagen formation by evaluating collagen synthesis or breakdown and the pool sizes of constituent amino acids (e.g., proline) through the use of radiolabeled tracers. MRI methods of monitoring the moment-to-moment changes of segments of the heart wall use a saturating radio frequency pattern such that a null-signal grid appears on the MRI image set. The motion of this grid reflects the twisting, contraction, and dilation of individual sectors of the muscle. This motion allows quantitation of the spatial distribution of the strain tensor and gives quantitative evidence of the progression of the congestive heart failure as well as measures the efficacy of treatments. Thus, the engineering of radioactive molecules to be probes of collagen remodeling, the perfection of emission tomography methods of imaging the beating heart, and MRI imaging of the strain tensor allow an approach to understanding one of the major health care problems facing the nation.

New methods of PET, ultrasound imaging, and MRI have brought major advances to cancer detection.

Contemporary methods for detecting and staging human cancers rely heavily on X-ray imaging, particularly for cancers of the lungs, bones, and gastrointestinal tract, where the imaging techniques are used as an adjunct to the symptom-related evaluation of patients. Conventional projection X-ray imaging can be diagnostic in some cancers, but usually more specialized procedures using X-ray CT or X-rays with fluoroscopy during infusion of contrast material, such as barium enema, are used. The new methods of PET, ultrasound imaging, and MRI have brought major advances to cancer detection.

Breast cancer is an example of a problem that begs for new engineering solutions. Digital mammography (Feig and Yaffe, 1995) has not made many expected clinical advances despite the electrical engineering applied to this problem. This is because the intrinsic contrast between diseased tissue and normal tissue is only 1 percent or less. On the basis of suspicious mammograms there are 700,000 biopsies of breast tissue annually, but in only 35 percent of cases is cancer actually present. Thus, some other method is needed to select patients for biopsy.

Breast cancer is an example of a problem that begs for new engineering solutions.

A new technology for studying breast cancer involves use of cancer-specific radiopharmaceuticals. For example, by using the radionuclide fluorine-18 attached to deoxyglucose and a PET instrument, it is possible to scan the whole body for evidence of cancer and metastases distant from the cancer and to evaluate the effectiveness of therapies. Another new engineering technology being applied to breast images is the use of solid-state components to create an inexpensive compact gamma camera that promises to significantly aid early breast cancer diagnosis (Gruber et al., 1998).

Arthritis

In one way or another, arthritis and osteoporosis affect 13 million people in the United States. Specialized applications of the major imaging methods are being focused on these problems. MRI can detect cartilage and bone matrix changes and has provided a cost-effective substitute for X-ray methods such as myelography. PET can determine the role of the immune system and potentially the metabolism of collagen, which is the scaffold on which bone is formed. X-ray CT can now provide almost real-time three-dimensional images of joints and defects in the neck and back vertebrae.

It appears that stresses in the intervertebral discs result in a disruption of the collagen supporting sheath. These stresses are accompanied by changes of the material within discs that controls electrolyte concentrations important for proper osmotic pressures. The need to understand vertebral disease early in life can be fulfilled by engineering MRI magnets that allow dynamic imaging under load-bearing conditions as well as access to patients for image-guided surgery.

Visualization and Virtual Reality

Image multiplexing (or fusion), image-guided therapy, and virtual reality in human imaging are three current activities in signal processing and visualization that are important to medical science. Straightforward methods of image processing have allowed the superposition of multimodality imaging methods (e.g., MRI and PET) in a presentation of fused images. Although there is no evidence that fusion images have led to major advances in clinical diagnoses, these methods have enabled the image-guided therapy that is playing a prominent role in medical practice. The major engineering innovations involve construction of a new type of MRI magnet that allows open access to the patient during surgical manipulations, such as tumor biopsy. This approach, pioneered by General Electric Corporation, promises to have a significant impact on the efficacious practice of medicine.

One of the most exciting innovations in biomedical imaging is the application of virtual reality to the day-to-day clinical study of human disease. Many years ago, the movie *Fantastic Voyage* presented the concept of visualizing the body from the inside, traversing blood vessels as though they were freeways. The ability to visualize the anatomy and function of the body by noninvasively entering a three-dimensional image data set and exploring it from the inside out would realize the clinician's dream of dissecting the living body without knife, needle, endoscope, or injury. This dream is now being realized by virtual colonoscopy in day-to-day clinical practice, and potentially will be available for bronchoscopy and even spinal canal and vertebral foramen exploration.

Through innovations such as spiral CT (Kalender et al., 1990) and MRI, three-dimensional data can be collected in only a few minutes without patient discomfort. Modern, low-cost computers can manipulate three-dimensional data sets using newly developed software. This technology of visualization can dramatically change the practice of medicine as it enables new approaches to understanding cancer of lungs and colon, aortic diseases, spinal stenosis, and lower-back pathologies, which are expected to increase in prevalence in the aging population of the United States.

New developments will continue in the future of biomedical instrumentation for medical imaging. These developments are stimulated by the desire to visualize and quantitate functions of the human body and are enabled by advances spanning electrical, mechanical, and chemical engineering, and the computer and materials sciences. The professional engineers and scientists who will create the future are from these disciplines and the integration of these disciplines is a primary example of the evolving field of bioengineering.

Acknowledgments

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NAE News and Notes

NAE Newsmakers

Thomas R. Anthony, staff physicist, General Electric Corporate Research and Development Center, received the 1999 **James C. McGroddy Prize in New Materials** from the American Physical Society (APS) "for innovation in growing diamond and germanium crystals with unprecedented control of chemical and isotopic purity and perfection, and for creative leadership and active participation in worldwide collaborations based on these extraordinary materials resulting in both fundamental discoveries and new technological applications."

Willard S. Boyle, consultant, AT&T Bell Laboratories, and **George E. Smith,** retired head, MSO Device Department, AT&T Bell Laboratories, jointly received the 1999 **C&C Prize** and the first **Breakthrough Award** from the Device Research Conference for their work on charge-coupled devices, which turn patterns of light into useful information and are used in facsimile and copying machines, image scanners, digital still cameras, bar code readers, telescopes, and televisions.

Foreign Associate **Hendrik B. G. Casimir,** emeritus professor, Leiden University, received the APS's 1999 **George E. Pake Prize** "for excellence as a leader of industrial research at Royal Philips Electronics and for fundamental contributions to the foundations of quantum mechanics and solid state physics."

Mildred S. Dresselhaus, Institute Professor of Electrical Engineering and Physics, Massachusetts Institute of Technology, received the 1999 **Nicholson Medal for Humanitarian Service** from the APS. The medal was awarded to her "for being a compassionate mentor and lifelong friend to young scientists; for setting high standards for researchers, teachers, and citizens; and for promoting international ties in science."

Daniel C. Drucker, graduate research professor of engineering sciences, emeritus, University of Florida, has been awarded the first **Panetti-Ferrari International Prize and Gold Medal** by the Academy of Sciences of Turin, Italy, for his distinguished research in applied mechanics.

Mary L. Good, managing member, Venture Capital Investors, LLC, received the 1999 **Heinz Award in Technology, the Economy and Employment** for "her singular vision in working to build an economy fueled by scientific knowledge and technological know-how."

Daniel D. Joseph, Regents Professor and Russell J. Penrose Professor of Aerospace Engineering and Mechanics, University of Minnesota, was presented the APS's 1999 **Fluid Dynamics Award** for outstanding achievement in fluid dynamics research.

Arthur Kantrowitz, professor of engineering, Dartmouth College, delivered the keynote address at the International Forum on Advanced High-Power Lasers and Applications in Osaka, Japan, during fall 1999. Dr. Kantrowitz's talk, titled "Then and Now," highlighted attitudinal perceptions of scientific advancement and public policy.

J. David Lowell, manager of Lowell Mineral Exploration, LLC, Rio Rico, Arizona, was the first recipient of the **Robert Dreyer Award** at the annual meeting of the Society of Mining Engineers of the American Institute of Mining Engineers (AIME) at Salt Lake City, Utah, on 1 March 2000. On 17 March he also received the AIME **Earll McConnell Award** for excellence in mining engineering at the AIME annual meeting in Nashville, Tenn. In April Mr. Lowell served as the **Foreign Exchange Lecturer** for the Society of Economic Geologists and delivered 12 lectures in universities and government centers in Australia and New Zealand.

Angelo Miele, Foyt Professor Emeritus of Engineering, Aerospace Sciences, and Mathematical Sciences at Rice University, has been elected **Honorary Fellow** of the American Institute of Aeronautics and Astronautics "for analytical, computational, and educational contributions to the fields of atmospheric and space flight mechanics, centered on optimization, guidance, and control of aircraft and spacecraft trajectories."

Arun G. Phadke, American Electric Power Professor of Electrical Engineering, Virginia Polytechnic Institute and State University, received the IEEE **Herman**

Halperin Electric Transmission and Distribution Award for leadership in the field of computer relaying and for the concept of synchronized phaser measurement used in GPS satellite signals.

Calvin F. Quate, Leland T. Edwards Professor of Electrical Engineering, Stanford University, and **H. Kumar Wickramasinghe,** manager, imaging science and measurement technology, IBM Thomas J. Watson Research Center, have received the 2000 **Joseph F. Keithley Award** from the APS "for pioneering contributions to nanoscale measurement science through their leadership in the development of a range of nanoscale force microscopes that have had major impact in many areas of physics."

Eli Reshotko, Kent H. Smith Professor of Engineering, Case Western Reserve University, received the 1999 **Otto Laporte Award** from the APS "for lasting contributions and leadership to the understanding of transition to turbulence in high-speed flows and non-homogeneous flows."

Walter A. Rosenblith, Institute Professor Emeritus, Massachusetts Institute of Technology, received the **Okawa Prize** on 25 November 1999 for outstanding contributions to the progress of biomedical engineering, auditory biophysics, and the promotion of international scientific cooperation.

Elbert L. Rutan, president and CEO, Scaled Composites, Inc., received the 2000 **Lindbergh Award.** Mr. Rutan is cited for leading the engineering design, construction, and testing of a series of remarkable aircraft, including the Voyager, the first unrefueled aircraft to circle the Earth.

Milton C. Shaw, professor of engineering, emeritus, Arizona State University, was presented the Japan Society for Precision Engineers **International Prize.** Professor Shaw was recognized for his achievements in precision engineering at a ceremony held in Tokyo in fall 1999.

Chauncey Starr, president emeritus, Electric Power Research Institute, will receive the APS 2000 **George E. Pake Prize** "for visionary leadership and physics contributing to the establishment of a worldwide nuclear power industry for peaceful purposes."

Kenneth N. Stevens, professor of engineering, Massachusetts Institute of Technology, received the **National Medal of Science** in engineering on 14 March 2000 "for pioneering contributions to the theory, mathematical methods, and analysis of acoustics in speech production, and for establishing the contemporary foundations of speech science."

Frank E. Talke, professor of mechanical engineering, University of California, San Diego, was one of 12 recipients of the 1999 **Max Planck Research Award.** Dr. Talke was recognized for his research in microtribology and design systematics of magnetic storage systems at a ceremony held at the Max Planck House at Hofgarten in Munich.

Robert W. Taylor, director emeritus, Systems Research Center, Compaq Computer Corp., received the 1999 **National Medal of Technology** on 14 March 2000 for his visionary leadership in the development of modern computing technology, including ARPAnet, the personal computer, and the graphical user interface.

Joseph F. Traub, Edwin Howard Armstrong Professor, Columbia University, received the 1999 **Mayor's Award for Excellence in Science and Technology.** Dr. Traub was presented with the award by Mayor Rudolph Giuliani in a recent ceremony in New York City.

Richard T. Whitcomb, retired distinguished research associate, NASA Langley Research Center, received the **NAS Award in Aeronautical Engineering** on 1 May 2000 during the NAS annual meeting "for his pioneering contributions to the aerodynamic design of high-performance aircraft."

Sheila E. Widnall, Institute Professor, Massachusetts Institute of Technology, received the **James V. Hartinger Award** from the National Defense Industrial Association in August 1999. Dr. Widnall was cited for her achievements as Secretary of the Air Force and also for integrating space systems into national defense policy, space-based infrared sensors, and new launch vehicles that are expendable.

Class of 2000 Elected

The National Academy of Engineering has elected 78 engineers and 8 foreign associates to membership in the Academy. This brings the total U.S. membership to 2,027 and the number of foreign associates to 157.

Election to the NAE is among the highest professional distinctions accorded an engineer. Academy membership honors those who have made "important contributions to engineering theory and practice, including significant contributions to the literature of engineering theory and practice," and those who have demonstrated "unusual accomplishment in the pioneering of new and developing fields of technology."

A list of the newly elected members and foreign associates follows, with their primary affiliations at the time of election and a brief statement of their principal engineering accomplishments.

Members

Frances H. Arnold, professor of chemical engineering and biochemistry, division of chemistry and chemical engineering, California Institute of Technology, Pasadena. For integration of fundamentals in molecular biology, genetics, and bioengineering to the benefit of life science and industry.

James P. Bagian, director, Veterans Administration National Center for Patient Safety, Ann Arbor, Mich. For integration of engineering and medical knowledge in applications to aerospace systems, environmental technology, and patient safety.

Clyde N. Baker, Jr., senior principal engineer, STS Consultants Ltd., Vernon Hills, Ill. For advancements in the engineering and construction of deep foundations for safe support of the world's tallest buildings.

Tamer Basar, Fredric G. and Elizabeth H. Nearing Professor of Electrical and Computer Engineering, University of Illinois, Urbana-Champaign. For development of dynamic game theory and application to robust control of systems with uncertainty.

James R. Bassingthwaighte, professor of bioengineering, biomathematics, and radiology, University of Washington, Seattle. For contributions to integrative physiology and bioengineering using transport theory and computational methods.

Howard R. Baum, fellow, Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, Md. For developing and implementing broadly applicable analytical models and numerical tools for understanding and mitigating fire phenomena.

James F. Blinn, graphics fellow, Microsoft Research, Redmond, Wash. For contributions to the technology of educational use of computer graphics and for expository articles.

Seth Bonder, president, chief executive officer and founding member, Vector Research Inc., Ann Arbor, Mich. For technical and organizational leadership in military and civilian operations research.

Ned H. Burns, Zarrow Centennial Professor of Engineering, department of civil engineering, University of Texas, Austin. For contributions to development and education in prestressed concrete including unbonded tendon building slabs and high-performance concrete bridges.

Edwin E. Catmull, executive vice president and chief technology officer, Pixar Animation Studios, Richmond, Calif. For leadership in the creation of digital imagery, leading to the introduction of fully synthetic visual effects and motion pictures.

James W. Cooley, adjunct professor, electrical engineering department, University of Rhode Island, Kingston. For the creation and development of the Fast Fourier Transform (FFT) algorithm for time series analysis.

W. Gene Corley, vice president, Construction Technology Laboratories, Skokie, Ill. For leadership in raising the standards of the engineering profession for construction of buildings and bridges.

Charles R. Cutler, senior adviser, Aspen Technology, Port Arkansas, Texas. For invention, development, and commercial implementation of a new-generation digital process control technology.

David E. Daniel, professor and head, department of civil and environmental engineering, University of Illinois, Urbana-Champaign. For leadership in developing the geoenvironmental engineering field, and major contributions to engineering practice involving landfills and waste containment systems.

Pablo G. Debenedetti, Class of 1950 Professor in Engineering and Applied Science, department of chemical engineering, Princeton University, Princeton, N.J. For microscopic theory and application of supercritical and metastable fluids.

Richard E. DeVor, Grayce Wicall Gauthier Professor of Mechanical and Industrial Engineering, University of Illinois, Urbana-Champaign. For contributions to the field of manufacturing research and its applications.

Michael Ettenberg, corporate senior vice president, Sarnoff Corp., Princeton, N.J. For contributions to the advances in optoelectronic components, including the evolution of practical and reliable semiconductor lasers.

Delores M. Etter, deputy undersecretary of defense of science and technology, Office of the Secretary of Defense, Washington, D.C. For the authorship of textbooks on computer applications in engineering, contributions to digital signal processing, and service to the profession.

Millard S. Firebaugh, vice president of advanced development, Electric Boat Corp., Groton, Conn. For innovation and U.S. Navy leadership in submarine design, propulsion, and construction.

Jean M. J. Fréchet, professor, College of Chemistry, University of California, Berkeley. For contributions to the discovery, development, and engineering of new materials for microlithography and separation technologies.

Ivan T. Frisch, executive vice president and provost, Polytechnic University, Brooklyn, N.Y. For innovation and implementation of data, voice, and integrated communication networks.

Charles D. Greskovich, senior research and development scientist, General Electric Research and Development Center, Niskayuna, N.Y. For innovations in technical ceramics and their manufacturing processes.

Ignacio E. Grossmann, Rudolph R. and Florence Dean Professor of Chemical Engineering, Carnegie Mellon University, Pittsburgh. For leadership in mixed integer nonlinear programming (MINLP) model formulation and solution for process design and operation.

Larry L. Hench, associate director, Interdisciplinary Research Center in Biomedical Materials, and professor of ceramic materials, Imperial College of Science, Technology, and Medicine, University of London. For the development of bioactive glasses for human prostheses and fundamental studies of glass corrosion.

John P. Holdren, Teresa and John Heinz Professor of Environmental Policy, John F. Kennedy School of Government, Harvard University, Cambridge, Mass. For articulation of energy environmental and proliferation issues.

Norden E. Huang, research oceanographer, Laboratory of Hydrospace Processes, NASA Goddard Space Flight Center, Greenbelt, Md. For contributions to the analysis of nonlinear stochastic signals and related mathematical applications in engineering, biology, and other sciences.

Srinivasa H. Iyengar, consultant, Skidmore, Owings, Merrill, Evanston, Ill. For leadership and contributions in structural design of tall buildings and long-span structures and advances in fire-resistive construction.

Forrester T. Johnson, manager, Boeing Co., Seattle. For the development of CFD codes bringing aerodynamic modeling of complex configurations within the means and capabilities of project engineers.

Randy H. Katz, professor of electrical engineering and computer science, University of California, Berkeley. For contributions to high-performance input/output systems, engineering education, and government service.

David M. Kelley, founder and chief executive officer, IDEO Product Development, Palo Alto, Calif. For creation of products of diversity and for affecting the practice of design.

Justin E. Kerwin, professor of naval architecture, Massachusetts Institute of Technology, Cambridge. For research and development of computational methods used in propeller design and in the prediction of sailing yacht performance.

Albert I. King, distinguished professor of mechanical engineering, Wayne State University, Detroit. For advances in understanding the mechanism, response, and tolerance of the human body to normal and traumatic loading.

Jack L. Koenig, professor of macromolecular science and the Donnell Institute Professor, Case Western Reserve University, Cleveland. For applications of spectroscopic methods of polymeric materials.

William J. Koros, B. F. Goodrich Professor in Materials Engineering, department of chemical engineering, University of Texas, Austin. For innovations in new materials and membrane structures for separation of gas mixtures.

Don Kozlowski, former senior vice president, military transport aircraft, McDonnell Douglas (now the Boeing Co.), St. Louis. For effective program management in restructuring the C-17 program.

Way Kuo, Halliburton Professor and head, department of industrial engineering, Texas A&M University, College Station. For contributions to reliability design for microelectronics products and systems.

Shung-Wu (Andy) Lee, retired founder and head of DEMACO (now part of Science Applications International Corp.), Champaign, Ill. For contributions to the understanding of radar scattering from complex objects and stealth aircraft technology.

Frederick J. Leonberger, vice president and chief technology officer, JDS Uniphase, Bloomfield, Conn. For contributions and leadership in the development and applications of integrated optics modulators.

Octave Levenspiel, professor emeritus, department of chemical engineering, Oregon State University, Corvallis. For contributions in chemical reaction engineering and introducing these into the profession as a cornerstone of the basic curriculum.

Nancy G. Leveson, professor of aerospace information systems, Massachusetts Institute of Technology, Cambridge. For contributions to software safety.

Y. K. Lin, Charles E. Schmidt Eminent Scholar Chair in Engineering and director, Center for Applied Stochastics Research, Florida Atlantic University, Boca Raton. For research contributions to the theory of stochastic dynamics and its applications to engineering structures.

Cecil Lue-Hing, director of research and development, Metropolitan Water Reclamation District of Greater Chicago. For contributions to the practice of water pollution control engineering, particularly biosolids management.

Noel C. MacDonald, professor, department of mechanical and environmental engineering, University of California, Santa Barbara. For contributions to the development of the scanning auger microprobe and micromachined micro-instruments.

Henry (Harry) McDonald, director, NASA Ames Research Center, Moffett Field, Calif. For leadership of a major national aeronautical laboratory, development of the block implicit method for CFD, and co-invention of a valuable medical-assist device.

William J. McNutt, consultant, Pittsfield, Mass. For contributions to the design and development of large power transformers.

Dane A. Miller, president and chief executive officer, Biomet Inc., Warsaw, Ind. For outstanding contributions to the orthopedic implant industry, for successfully creating a multinational corporation, and for unparalleled leadership in the biomedical engineering community.

Peter F. Moulton, chief technology officer and senior vice president, Q-Peak Inc., Bedford, Mass. For the titanium sapphire laser and the technology of all-solid-state, turnable, and ultrashort-pulse laser systems.

Alan Needleman, professor, solid mechanics group, division of engineering, Brown University, Providence, R.I. For research in computational solid mechanics and its application to damage and fracture mechanics.

Donald R. Olander, professor, department of nuclear engineering, University of California, Berkeley. For research on nuclear materials including nuclear fuel element behavior in power reactors.

Franklin M. Orr, Jr., dean, School of Earth Sciences, Stanford University, Stanford, Calif. For contributions to understanding of complex multicomponent flows in porous media and its applications to the design of enhanced oil recovery processes; and for superb academic leadership.

Yih-Ho Michael Pao, retired chairman and chief executive officer, Waterjet International Inc., Houston. For research, development, and commercialization of water-jet technology for machining, trenchless boring, and surface preparation.

Celestino R. Pennoni, chairman of the board and chief executive officer, Pennoni Associates Inc., Philadelphia. For advancing innovative principles in the art and science of engineering, engineering education, and engineering management.

Edward W. Price, Regents' Professor Emeritus, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta. For critical contributions to the understanding of solid propellant combustion and solid rockets developments.

Henry H. Rachford, Jr., principal technical adviser, Stoner Associates Inc., Houston. For contributions in the numerical solution of partial differential equations to solve petroleum reservoir and pipeline hydraulics problems.

Kenneth J. Richards, president, Alta International Inc., Edmond, Okla. For contributions in the development of advanced copper smelting technology.

Robert L. Sackheim, assistant director, space propulsion systems, NASA Marshall Space Flight Center, Huntsville, Ala. For contributions to space and missile propulsion technology and programs.

Stuart B. Savage, professor emeritus of civil engineering and applied mechanics, McGill University, Montreal. For contributions to the mechanics of granular flows that have laid the foundation for wide-ranging applications of particle technology.

Jacob T. Schwartz, mathematics and computer science professor, Courant Institute, New York University, New York City. For contributions to the theory and practice of programming language design, compiler technology, and parallel computation.

Shirley E. Schwartz, retired senior staff research scientist, General Motors Research and Development Center, Warren, Mich. For contributions to lubrication engineering and for enriching the technical community through freelance writing.

Hratch G. Semerjian, director, Chemical Science and Technology Laboratory, National Institute of Standards and Technology, Gaithersburg, Md. For developing powerful laser diagnostics of flames, and for providing measurement methods, standards, and data to the chemical and biochemical industry.

Daniel Shechtman, distinguished professor, department of materials engineering, Technion, Haifa, Israel. For the discovery and characterization of quasi-crystals.

Hanif D. Sherali, Charles O. Gordon Endowed Professor of Industrial and Systems Engineering, Virginia Polytechnic Institute and State University, Blacksburg. For engineering system design based on optimization theory.

Daniel P. Siewiorek, Buhl Professor of Electrical and Computer Engineering and Computer Science, Carnegie Mellon University, Pittsburgh. For contributions to wearable computers, multiprocessor design, reliable systems, and automated design synthesis.

Marwan A. Simaan, Bell of Pennsylvania/Bell Atlantic Professor of Electrical Engineering, University of Pittsburgh. For contributions to the development of signal processing techniques for imaging the Earth's subsurface zone.

W. David Sincoskie, vice president, Internet Architecture Research Laboratory, Telcordia Technologies (formerly Bellcore), Morristown, N.J. For contributions in packet switching for integrated networks.

Robert M. Sneider, president, Robert M. Sneider Exploration Inc., Houston. For teaching and demonstrating the importance of synergistic geological, geophysical, and engineering efforts in the exploration and development of hydrocarbon accumulations.

Dean E. Stephan, retired president, Charles Pankow Builders Ltd., Altadena, Calif. For leadership and innovation in design and construction of advanced concrete technology.

Gerald J. Sussman, Matsushita Professor of Electrical Engineering, department of electrical engineering and computer science, Massachusetts Institute of Technology, Cambridge. For applications of artificial intelligence and for computer science education.

Jerome Swartz, chairman and chief executive officer, Symbol Technologies Inc., Holtsville, N.Y. For bar code technologies, including laser scanners and wireless data capture.

Richard H. Truly, director, U.S. Department of Energy's National Renewable Energy Laboratory, Golden, Colo. For leadership and personal contributions in the advancement of national civil and military space programs.

John J. Vithayathil, engineering consultant, Portland, Ore. For the invention of thyristor-controlled series capacitor system and advancement of HVDC transmission technology.

Alan M. Voorhees, chairman, Summit Enterprises of Virginia Inc., Woodbridge. For the discovery and application of the quantitative relationships between urban land uses and traffic flows.

Rong-Yu Wan, manager of metallurgical research, Newmont Mining Corp., Newmont Technical Facility, Englewood, Colo. For accomplishments in metallurgical research and industrial practice, and for teaching, supervising, and inspiring students, researchers, and industrial colleagues.

Garret P. Westerhoff, chairman and chief executive officer, Malcolm Pirnie Inc., White Plains, N.Y. For leadership in the application of new technologies for drinking water treatment and for international contributions to utility management.

John J. Wetzel II, vice president and general manager, NAO Technical Centers, General Motors Corp., Warren, Mich. For creating a simultaneous engineering environment where manufacturing and design engineering teams concurrently design product and process.

Dennis F. Wilkie, corporate vice president and director, business development, quality and staff operations, integrated electronic systems sector, Motorola Inc., Northbrook, Ill. For the application of electronics and systems engineering technology to vehicular systems.

C. P. (Ching-Ping) Wong, professor, materials science and engineering, Georgia Institute of Technology, Atlanta. For contributions to materials development leading to plastic packaging of electronics.

Joseph A. Yura, Warren S. Bellows Centennial Professor in Civil Engineering, University of Texas, Austin. For research and educational contributions on bracing and stability design for steel structures.

Foreign Associates

Chun-Yen Chang, president, National Chiao Tung University, Kaohsung, Taiwan. For contributions to the Taiwanese electronics industry, education, and materials technology.

Luis Esteva, professor, Institute of Engineering, National University of Mexico, Mexico City. For contributions to seismic design and reliability analysis of structures and for leadership in international earthquake engineering activities.

Kazuo Inamori, founder and chief executive officer emeritus, Kyocera Corp., Kyoto, Japan. For innovation in ceramic materials and solar cell development and manufacturing; entrepreneurship of advanced technologies; and for being a role model for relating science to society.

Helmut List, president and chief executive officer, AVL List GMBH, Graz, Austria. For building a world-class, technology-based international engineering, scientific, and research corporation.

Hajime Sasaki, chairman, NEC Corp., Tokyo. For contributions and leadership in development of advanced very large scale integration (VLSI) systems and in growth and harmonization of the international semiconductor industry.

Jian Song, president, Chinese Academy of Engineering Sciences, Beijing. For contributions to aerospace engineering, environmental protection, science and technology administration, and fostering international technical cooperation.

Andreas Von Bechtolsheim, vice president of engineering, Cisco Systems Inc., San Jose, Calif. For contributions to the design of computer workstations and high-performance network switching.

James H. Whitelaw, professor of convective heat transfer, department of mechanical engineering, Imperial College of Science, Technology, and Medicine, University of London. For contributions to fluid mechanics, heat transfer, and combustion instrumentation, and to education and the dissemination of new information.

K–12 Standards for Technological Literacy

In 1997, the NAE and the International Technology Education Association (ITEA) began informal discussions about the role of technology studies in elementary and secondary education. ITEA asked the NAE to review a set of content standards for K–12 technology education that ITEA was developing under funding from the National Science Foundation (NSF) and NASA. ITEA felt the standards would be strengthened by having the Academy's input. The NAE, for its part, saw the standards as a potentially effective tool for encouraging greater technological literacy.

The Academy established a six-person committee for this purpose, chaired by **George Bugliarello,** chancellor, Polytechnic University. Over the following year, the committee reviewed and provided comment on the first three drafts of the standards. The NAE committee was just one of many sources of input to ITEA. Altogether, more than 4,000 people critiqued the document through a variety of means, including mail-in review, online review, and input at field hearings around the United States.

In large measure because of the seriousness of the concerns about the third draft raised by key reviewers—including the NAE committee—ITEA concluded that the standards required additional revision. To that end, ITEA enlisted the expertise of the NRC Center for Science, Mathematics, and Engineering Education (CSMEE), which has a track record of developing educational standards for the K–12 grades. ITEA asked for and was awarded supplemental funding from NSF in March 1999 to carry out the additional review. The NAE committee decided to wait for this work to be finished before making a final judgment about the standards.

In October 1999, the NRC ITEA Standards Review Committee, chaired by NAE President **Bill Wulf,** issued its interim report. The report was encouraging about the progress made in the fourth draft of the standards, but it cited a number of areas where additional improvements were needed. (The report is available online at http://www.nap.edu/catalog/9763.html.) In late December 1999, after reviewing the fifth and sixth drafts, the NRC committee declared that the standards had met the requirements of the NRC report review process and issued a final letter report (also available online, http://www.nap.edu/catalog/9765.html).

Based on the conclusions of the NRC committee and their own positive assessment of the final draft of the standards, the NAE committee urged the NAE Council to make an affirming statement about the standards. The Council did so at its February meeting. (See below.)

The full text of the ITEA standards for technological literacy may be viewed online at the ITEA website, http://www.iteawww.org.

Statement on the ITEA Standards for Technological Literacy by the Council of the National Academy of Engineering

10 February 2000

The United States depends on technology to maintain the health of its citizens, the safety of its borders, the strength of its economy, and the smooth functioning of its government. Despite this dependence, U.S. society is largely ignorant of the nature, history, and processes of technology. The result is a public that is disengaged from the very decisions that are shaping our technological future.

This lack of technological literacy is of great concern. It both limits the range of opportunities available to individuals and increases the chances that we are assessing incompletely the potential benefits, as well as the potential risks, of technological development.

People gain an understanding of technology in a variety of ways, including through formal coursework in school. Carefully developed educational standards, such as *Standards for Technological Literacy: Content for the Study of Technology,* are a key tool for creating lasting, systemic educational improvement. These standards, developed by the International Technology Education Association (ITEA), suggest what all K–12 students should know and be able to do regarding technology. The standards represent an important step in developing technological literacy.

The standards are not a blueprint for developing new, stand-alone courses. In fact, much of the content of technology will need to be integrated across the existing curriculum—in math, science, social studies, language arts, art, music, and other subject areas. Nor are the standards meant to be the last word on technology education. Rather, they should be thought of as a living document subject to periodic reevaluation and revision.

The ITEA standards have undergone a lengthy development process, including a careful review by committees of both the National Academy of Engineering and the National Research Council.

The Council of the National Academy of Engineering strongly supports the *Standards for Technological Literacy: Content for the Study of Technology* and urges their implementation.

NAE Announces Greatest Engineering Achievements

Speaking on behalf of the NAE, astronaut and engineer **Neil A. Armstrong** announced the 20 engineering achievements that have had the greatest impact on quality of life in the twentieth century. The announcement was made 22 February during National Engineers Week at a sold-out National Press Club luncheon (see Armstrong's remarks on page 14).

To celebrate a remarkable century of technological achievement, the Greatest Achievements project was initiated by the NAE and conducted in collaboration with the American Association of Engineering Societies, National Engineers Week, and 27 other professional engineering societies. The societies generated more than 100 nominations for the list of the greatest achievements, and an NAE selection committee used an extensive evaluation process to choose and rank the top 20.

In conjunction with Armstrong's announcement, the NAE released a website highlighting the top 20 achievements. The website, www.greatachievements.org, lists the achievements, discusses their impact upon the quality of life, and provides brief histories of the key engineering events in their development.

The NAE's selection committee included leading engineering experts from academia, industry, and a wide range of engineering disciplines: **Harold M. Agnew,** retired president, General Atomics, and former director, Los Alamos National Laboratory; **Frances E. Allen,** IBM fellow; **Neil A. Armstrong,** former astronaut and chair, AIL Technologies; **Norman R. Augustine,** executive committee chair and former president and CEO, Lockheed Martin Corporation; **William F. Ballhaus, Sr.,** former president, Beckman Instruments; **David P. Billington,** author and professor of civil engineering and operations research, Princeton University; **Frederick H. Dill,** senior technical officer, IBM Research Center; **Essex E. Finney, Jr.,** retired, Agriculture Research Service, U.S. Department of Agriculture; **George M. C. Fisher,** chairman, Eastman Kodak Company, and former chairman and CEO, Motorola Inc.; **John H. Gibbons,** former assistant to President Clinton for science and technology, and former director, Office of Science and Technology Policy; **Daniel S. Goldin,** administrator, NASA; **Ronald E. Goldsberry,** chairman and CEO, CarStation.com; **Mary L. Good,** former under secretary for technology, U.S. Department of Commerce; **Irwin M. Jacobs,** chairman and CEO, QUALCOMM, Inc.; **Jack E. Little,** former president and CEO, Shell Oil Company; **Robert W. Lucky,** inventor of the adaptive equalizer used in high-speed data transmission; **John B. Mooney, Jr.,** U.S. Navy, retired, and former chief, Office of Naval Research; **William J. Perry,** former secretary of defense; **Henry Petroski,** author and professor of civil engineering, Duke University; **Alan Schriesheim,** former director and CEO, Argonne National Laboratory; **William E. Splinter,** inventor and developer of agricultural technologies; **H. Guyford Stever** (chair), former science advisor to President Ford, former president, Carnegie Mellon University, and former director, National Science Foundation; **Ivan E. Sutherland,** vice president and fellow, Sun Microsystems; **Paul E. Torgersen,** John W. Hancock, Jr., Chair in

Engineering and former president, Virginia Polytechnic Institute and State University; **Charles H. Townes,** inventor of maser/laser and Nobel laureate; **Charles M. Vest,** president, Massachusetts Institute of Technology; **John T. Watson,** acting deputy director, Heart, Lung, and Blood Institute, National Institutes of Health; **James C. Williams,** Honda Professor of Materials, Ohio State University; and **Wm. A. Wulf,** president, NAE.

Neil Armstrong's speech was broadcast on National Public Radio and C-SPAN, and the announcement was covered in *USA Today,* the *New York Times,* and a number of news websites, including CNN, MSNBC, ABC News, and Yahoo. For more information on the Greatest Achievements project, refer to the website at http://www.greatachievements.org, or contact Robin Gibbin at 202-334-1562 or rgibbin@nae.edu.

The Greatest Engineering Achievements of the 20th Century

1. Electrification
2. Automobile
3. Airplane
4. Water supply and distribution
5. Electronics
6. Radio and television
7. Agricultural mechanization
8. Computers
9. Telephone
10. Air conditioning and refrigeration
11. Highways
12. Spacecraft
13. Internet
14. Imaging
15. Household appliances
16. Health technologies
17. Petroleum and petrochemical technologies
18. Laser and fiber optics
19. Nuclear technologies
20. High-performance materials

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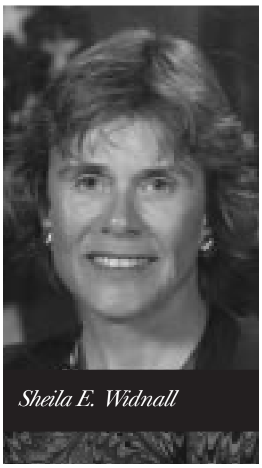


Sheila E. Widnall

The National Academy of Engineering has a long history of providing guidance to the nation's leaders on issues related to engineering and technology. As our society becomes increasingly dependent on technology, the NAE's ability to provide this guidance is more critical than ever.

The NAE's work is carried out in part through the support of National Research Council studies, and in part through independent, self-initiated program activities. To fulfill its mission, the NAE relies on the generosity of contributors to fund workshops, symposia, studies, and other activities.

In 1999, gifts received from members, individuals, foundations, and corporations totaled more than $1.7 million. When combined with new pledges made in 1999 for future gifts, the total exceeds $3.3 million. Corporate contributions to the NAE saw a nearly three-fold increase over 1998, with new, unrestricted gifts and pledges in excess of $1.8 million. Member giving also increased dramatically, with contributions to the NAE's Annual Fund reaching a record high of $340,000, an increase of 120 percent over 1998. (Total individual contributions for 1999, including those to the Annual Fund, reached $649,000.)

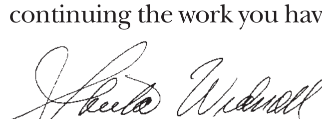
The total number of member gifts increased for the fourth consecutive year, and for the first time, the average donation exceeded $1,000. Former NAE Chairman Richard Morrow, retired CEO of Amoco, contributed the year's most significant individual gift, setting a strong leadership example in an exciting prelude to the Academy's upcoming capital campaign.

The NAE is profoundly grateful for this support. These funds allow the NAE to seed important engineering and policy initiatives throughout the National Academies. For example, between July 1998 and December 1999, the independent program of the NAE

- released two important new books related to industrial ecology—*Industrial Environmental Performance Metrics* and *Measures of Environmental Performance and Ecosystem Condition;*
- conducted a workshop at the request of the White House National Economic Council to explore the potential for using government-sponsored inducement prize contests to spur technological innovation;
- started a new program on technological literacy to encourage improvements in the U.S. education system and to guide the nation in this critical area;
- convened the Summit on Women in Engineering to focus attention on recruiting, retaining, and advancing women in engineering;
- held Frontiers of Engineering symposia for U.S. and German participants to facilitate collaboration and cross-discipline knowledge sharing among young engineers involved in leading-edge technical work; and
- expanded its efforts in outreach and public understanding of engineering with a number of new programs using diverse media outlets.

Despite these and other accomplishments, many challenges remain. We must continue to build upon the NAE's reputation as the preeminent organization for the resolution of society's most pressing technological issues. We also must work to promote professional and public awareness of the NAE and its role in our increasingly technology-driven society, and maintain a membership that is diverse, active, and recognized for its many accomplishments.

In the list below, the NAE gratefully acknowledges contributions received during the period from January 1 to December 31, 1999. We appreciate the trust you have placed in the NAE to accomplish an agenda that has distinct benefits for the engineering profession, our nation, and people worldwide, and we look forward to continuing the work you have so generously supported.



Sheila E. Widnall, NAE Vice President
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Massachusetts Institute of Technology

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Home Secretary Simon Ostrach Honored

L to R: Aaron Cohen, Si Ostrach, Kathie Olsen, Martin Glicksman, Eugene Trinh

On June 30 **Simon Ostrach** will conclude two terms as NAE Home Secretary. In honor of his service to the Academy membership, the National Meeting symposium, held on 11 February in Irvine, Calif., was dedicated to him. The symposium's theme, "The Space Program and Microgravity Research," was chosen to reflect Dr. Ostrach's extensive work in microgravity research, which included many experiments flown on space shuttle missions.

After an introduction by NAE President **Wm. A. Wulf,** the chair of the symposium organizing committee, **Aaron Cohen,** related the symposium's goals, which included expressing the NAE's deep respect and gratitude to Si for all he has done for the Academy. Kathie L. Olsen, NASA's chief scientist, delivered the keynote address, followed by Eugene H. Trinh, director of NASA's Microgravity Research Division, who spoke on "The Opportunities and Rewards of Low Gravity Investigations in the Physics of Fluid." The next topic was "Fluid Interactions in Crystal Growth and Solidification," discussed by **Martin E. Glicksman,** John Tod Horton Distinguished Professor, Rensselaer Polytechnic Institute. Charles Walker, senior manager of the space and communications group at Boeing, concluded the symposium by discussing "An Industry View of Low-Gravity R&D."

We wish Si all the best in his post as director of the National Center for Microgravity Research on Fluids and Combustion at Case Western Reserve University. We'll miss you, Si!

Draper Prize Winners Honored

Draper Prize recipients Charles K. Kao, Robert D. Maurer, and John B. MacChesney at the presentation ceremony hosted at the U.S. Depatement of State in Washington, D.C.

Neal Lane, assistant to the President for science and technology, represented the White House at a black-tie dinner in February to honor the recipients of the 1999 Charles Stark Draper Prize. The recipients are **Charles K. Kao, Robert D. Maurer,** and **John B. MacChesney,** key contributors to the development and manufacturing of fiber optic technology. In his remarks, Dr. Lane stated that "Today we live in an age of unparalleled possibility and prosperity that is built upon our national legacy of engineering achievements and innovations. From the automobile to space flight, from the telephone to the Internet, from electrification to nanotechnology, our unmatched engineers continue advancing the frontiers of discovery, transforming our lives and societies, and building a better world for the twenty-first century."

More than 250 guests attended the dinner and presentation ceremony hosted at the U.S. Department of State in Washington, D.C. NAE President **Wm. A. Wulf** served as master of ceremonies while **Mary Good,** chair of the 1999 Draper Prize committee, and Vince Vitto, president and CEO of the Charles Stark Draper Laboratory, discussed the committee selection process and provided a historical perspective on Charles Stark Draper, for whom the prize is named.

In 2001, the NAE's annual award dinner and presentation ceremony will honor the recipients of the Charles Stark Draper Prize as well as the first recipients of the Fritz J. and Dolores H. Russ Prize.

NAE Calendar of Meetings

2000

2 May	NAE Regional Meeting Princeton, N.J.
4 May	NAE Regional Meeting Cleveland
8–9 May	Convocation of Professional Engineering Societies
12 May	NAE Council
25 May	Draper Prize Committee
1 June	Committee on Engineering Education NAE/AAES International Advisory Committee
2 June	NAE/AAES Forum
7–8 June	Workshop on Megacities
15 June	Russ Prize Committee
16 June	Congressional Luncheon
26–27 June	Exploratory Workshop on Earth Systems Engineering
6–7 July	Forum on Diversity in the Engineering Workforce
27 July	NAE Regional Meeting Stanford, Calif.

All meetings are held in the Academies Building, Washington, D.C., unless otherwise noted.

In Memoriam

PAUL BECK, 89, professor emeritus of metallurgy, University of Illinois at Urbana-Champaign, died on 20 March 1997. Professor Beck was elected to the NAE in 1981 for pioneering studies in deformation and textures of engineering alloys and in electronic and magnetic characterization of complex alloy systems.

ROBERT BROMBERG, 77, retired vice president, research and engineering, TRW Electronics and Defense, died on 25 January 1999. Dr. Bromberg was elected to the NAE in 1969 for contributions as a teacher and researcher and as an engineer and manager in national defense and space programs.

SIGVARD EKLUND, 88, director general, emeritus, International Atomic Energy Agency, died on 31 January 2000. Dr. Eklund was elected a foreign associate of the NAE in 1979 for contributions to the practical uses of atomic energy.

ROBERT C. GOODING, 81, director, Columbia Research Corporation, died on 30 November 1999. Admiral Gooding was elected to the NAE in 1976 for contributions to Polaris/Poseidon weapon systems and development of naval sea systems.

ARNOLD HALL, 84, retired chairman, Hawker Siddeley Group, PLC, died on 11 January 2000. Sir Arnold was elected a foreign associate of the NAE in 1976 for contributions in aeronautics, including design and construction of the first large-scale British transonic wind tunnel and other developments in aircraft navigation and structures.

EIVIND HOGNESTAD, 78, retired director, Construction Technology Laboratories, Inc., died on 16 February 2000. Dr. Hognestad was elected to the NAE in 1973 for contributions and leadership in reinforced concrete research, particularly ultimate strength design and the use of high-strength reinforcement.

MILO KETCHUM, 89, emeritus professor of civil engineering, University of Connecticut, died on 8 December 1999. Dr. Ketchum was elected to the NAE in 1982 for pioneering the development of folded-plate and thin-shell structures and their application to innovative, creative, and aesthetic designs.

FRITZ LEONHARDT, 90, independent consultant, died on 30 December 1999. Dr. Leonhardt was elected a foreign associate of the NAE in 1983 for contributions through research, teaching, and engineering practice to the art and science of designing long-span concrete bridges and high-rise towers, and for lectures and publications favorably influencing the public's image of engineering.

GERALD J. LIEBERMAN, 73, professor of operations research and statistics, Stanford University, died on 18 May 1999. Dr. Lieberman was elected to the NAE in 1987 for significant technical contributions to quality control and reliability, and for leadership as an engineering educator.

ALAN S. MICHAELS, 77, president, Alan Sherman Michaels, Sc.D., Inc., died on 16 January 2000. Dr. Michaels was elected to the NAE in 1979 for pioneering developments in the fields of surface, colloid, and polymer chemistry; membrane science and technology; and advanced systems for drug delivery to the human body.

KENNETH D. NICHOLS, 92, U.S. Army, retired, died on 21 February 2000. Major General Nichols was elected to the NAE in 1968 for contributions to hydraulic engineering; engineering and construction of Manhattan Project nuclear materials plants; and guidance of military weapons programs.

NUNZIO J. PALLADINO, 83, professor emeritus and dean emeritus, Pennsylvania State University, died on 12 December 1999. Dr. Palladino was elected to the NAE in 1967 for design and development of submarine and power reactors.

HAROLD SMITH, 80, retired vice president, Ontario Hydro, died on 6 January 2000. Dr. Smith was elected a foreign associate of the NAE in 1978 for contributions to the development of the CANDU nuclear reactor system as a major form of electric energy supply.

VITO VANONI, 95, professor emeritus of hydraulics, California Institute of Technology, died on 27 December 1999. Dr. Vanoni was elected to the NAE in 1977 for leadership in developing the science of hydraulic sedimentation mechanics and applying it to construction and maintenance of engineering structures.

WALTER H. ZINN, 93, retired vice president of Combustion Engineering, Inc., died on 14 February 2000. Dr. Zinn was elected to the NAE in 1974 for contributions to nuclear physics and reactor development.

National Research Council Update

Space Station Improvements Needed

According to a new NRC report, nothing in the design of the International Space Station should adversely affect long-term operations once construction is complete, but NASA should take steps to ensure that astronauts will have sufficient time to conduct the scientific experiments for which the station was intended. The report, **Engineering Challenges to the Long-Term Operation of the International Space Station,** questions whether daily maintenance on the assembled station will leave crews enough time for research, a problem that plagued the Russian space station Mir.

At the request of Congress, the NRC formed an expert committee to evaluate NASA's plans for supporting the space station after it is assembled. For the most part, the committee found the station's design to be sound. However, it expressed concern that NASA's focus on the assembly of the space station leaves the need for important planning on how best to conduct research, operate the station, upgrade equipment, and make repairs once the space station is functional. At the time of the committee's study, construction of the space station was scheduled for completion in November 2004, after which it would be operational for 15 to 20 years.

Most of the engineering deficiencies in the design of the space station can be corrected with procedural changes and equipment or software upgrades and can be addressed in time to meet the scheduled completion, the committee said. In the meantime, NASA should conduct a rigorous analysis of typical crew activities to determine if crews will have enough time to conduct research. The space agency also should take advantage of the long stints that flight crews will experience aboard the space station—as well as the ingenuity crews have historically shown—by delegating responsibility for much of the day-to-day scheduling to them.

The report recommends that NASA allow the astronauts carrying out experiments on the space station to exchange data and instructions directly with the principal investigators on the ground, evaluate how real-time video transmissions could facilitate repairs on board the space station, give higher priority to obtaining an appropriate crew return vehicle, and augment its plans for how astronauts will walk in space and use robotic arms outside the station in order to enhance the efficiency of crew members and ensure their safety. The committee also reviewed plans for decommissioning the space station and examined Russia's role in the project.

This report was authored by the Committee on the Engineering Challenges to the Long-Term Operation of the International Space Station of the NRC's Commission on Engineering and Technical Systems. **Thomas J. Kelly,** retired president of Grumman Corporation's Space Station Integration Division, chaired the committee, and **Jack L. Kerrebrock,** professor of aeronautics and astronautics at the Massachusetts Institute of Technology, served as a committee member. This report can be purchased or read online at http://books.nap.edu/catalog/9794.html.

Publications of Interest

The following publications result from the program activities of the National Academy of Engineering or the National Research Council. Except where noted, each publication is for sale (prepaid) from the National Academy Press (NAP), 2101 Constitution Avenue, N.W., Lockbox 285, Washington, DC 20055. For more information or to place an order, contact NAP online at http://www.nap.edu or by phone at (800) 624–6242. *(Note: Prices quoted by NAP are subject to change without notice. Online orders receive a 20 percent discount. Please add $4.50 for shipping and handling for the first book ordered and $0.95 for each additional book. Add applicable sales tax or GST if you live in CA, DC, FL, MD, MO, TX, or Canada.)*

Concerning Federally Sponsored Inducement Prizes in Engineering and Science. Reviews the use of inducement prize contests to advance technical innovation. Recommends that Congress encourage federal agencies to experiment with using inducement prize contests to support technology research and development. Paperbound, available from the NAE Program Office (202–334–1579).

Engineering Challenges to the Long-Term Operation of the International Space Station. Assesses operational issues after assembly of the space station, which is scheduled to be completed in 2004. Topics include maintenance and repair; astronaut work outside the station; equipment upgrades; use of an international fleet of launch vehicles to support the station; and decommissioning and removing the facility from orbit at the end of its useful life. Paperbound, $18.00.

Female Engineering Faculty at U.S. Institutions: A Databook. Contains statistical information about the education and employment of women on engineering faculties. Paperbound, $36.00.

Frontiers of Engineering: Reports on Leading Edge Engineering from the 1999 NAE Symposium on Frontiers of Engineering. Presents extended summaries of the presentations given at the October 1999 symposium on topics that include the human genome, engineering novel structures, and energy for the future and its environmental impact. Paperbound, $31.00.

Materials Science and Engineering: Forging Stronger Links to Users. Through case studies in the electronics, automotive, and jet-engine industries, this report examines the barriers to improving innovation and integration of materials users with materials scientists, engineers, and producers. Paperbound, $29.00.

Measuring the Nation's Science and Engineering Enterprise: Priorities for the Division of Science Resources Studies. Investigates the policy, planning, and research needs of those who use national and international data on science and engineering human resources and R&D expenditures, performance, and outcomes from the Science Resources Studies (SRS) division of the National Science Foundation. The report assesses the analysis activities of SRS and provides priorities and options for revising those activities to improve the usefulness of SRS data and publications. Paperbound, $34.75.

Nature and Human Society: The Quest for a Sustainable Future. Over the next hundred years, two-thirds of all life forms on Earth face extinction, largely because of uncontrolled development by humans. In this summary of the second National Forum on Biodiversity, the world's leading experts in the field describe the crisis ahead and the need to build a sustainable world in which animals, plants, fungi, microorganisms, and people can coexist harmoniously. Hardcover, $79.95.

Observations on the President's Fiscal Year 2001 Federal Science and Technology Budget. This is the third in a series of annual analyses that track trends in federal funding of science and technology research programs and facilities, and call attention to issues of concern to the scientific and engineering communities. Paperbound, $12.00.

Surviving Supply Chain Integration: Strategies for Small Manufacturers. Internet technologies and the integration of supply chains are creating revolutionary changes in manufacturing. This report examines the impact of state-of-the-art supply chain integration concepts and requirements on small and medium manufacturing enterprises and suggests strategies to improve their competitiveness. Hardcover, $35.95.