Winter 2002

The BRIDGE

LINKING ENGINEERING AND SOCIETY

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NATIONAL ACADEMY OF ENGINEERING
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The BRIDGE

NATIONAL ACADEMY OF ENGINEERING

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The BRIDGE

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Editorial

George Bugliarello is chancellor of Polytechnic University in Brooklyn, New York, and an NAE member.

The Expanding Frontiers of Engineering

Every year the NAE Frontiers of Engineering Symposium brings together young engineers working on cutting-edge technologies in many different fields. Papers delivered at the eighth symposium this year at the Beckman Center of the National Academies in Irvine, California, dealt with four themes: chemical and molecular engineering; technology for human beings; the future of nuclear energy; and engineering challenges for quantum information technology. The six papers published here we believe will be of special interest to our readers—NAE members, members of Congress, and other decision makers in government and industry. All 15 papers (including the papers published here) and a broad historical overview of digital communication delivered by **Andrew Viterbi** will be published in full early next year by the National Academies Press in a new *Frontiers of Engineering* volume. In this editorial, I would like to underscore some of the major issues raised in the symposium.

In the area of chemical and molecular engineering, one speaker emphasized the significant differences between nanocluster properties and their corresponding macro properties, which have opened up a range of innovative nanotechnologies. Our understanding of the properties of amorphous polymeric nanoclusters is still limited, however, and this is bound to be an important area of research in the future. Another talk focused on the continuing quest for cleaner, more efficient energy generation. Fuel cells, which can have very high theoretical efficiencies, have been slow to be commercialized, even though the concept is more than a century old. The two approaches most frequently considered are polymer electrolyte membrane (PEMs) fuel cells and sulfur solid-oxide electrolyte fuel cells (SOFCs). SOFCs, which are the more fuel flexible of the two, could use any combustible gas, at least in theory, and thus would not need a new fuel supply infrastructure.

In a paper published in this issue, David Davidson describes how computational fluid mechanics can be used to solve important industrial problems. At this juncture, however, the technology is still mostly in the domain of experts, very few of whom are in industry, so applications are limited. The situation could be remedied by closer interactions between experts in universities and industry.

The papers in the area of human factors dealt with a variety of topics. Kim Vicente (in a paper published here) recommends changes in engineering curricula to focus attention on interfaces between the technical and human sciences and the importance of human factors in the design process. Another speaker emphasized the role of human factors in transportation. Human factors are the most frequent causes of car crashes, which kill more than 40,000 Americans annually. To deal with this problem, we need to overcome current limitations in collecting and analyzing data about driver behavior and the influence of automotive skills, distractions, and driver judgment. Another speaker addressed the importance of human factors in the design of interfaces between software and users. Lack of attention to user needs can lead to frequent calls for customer service, increases in product returns, and general dissatisfaction among customers. A stronger focus on human factors could obviate many of these problems, shorten development times, and lead to more innovative products.

One presentation in the human factors area focused on the development of direct brain-computer interfaces for disabled people, one of the most fundamental challenges in human-machine interaction. In direct brain-computer interfaces, computers and devices are activated by direct action of the brain rather than by muscle movements. Although considerable progress has been made, we still have a long way to go to help victims who have normal brain function but are imprisoned in their bodies by disease.

The enormous potential of nuclear energy has not been realized because of concerns about safety, the management and disposal of nuclear waste, and the proliferation of weapons-grade materials. Peter Hastings (published here) discusses the programs that explore complete nuclear energy systems, including the recycling of spent fuel. The United Kingdom, France, Japan, and Russia already recycle fuel; the United States is the only country that still uses a single-cycle, once-through technology. The expansion of nuclear power generation in this country will require more efficient licensing and regulatory processes and a revitalized supply chain. Marvin Adams addresses the potential of nuclear fission to provide sustainable, reliable energy for centuries to come. Adams also makes a strong case for the recycling of nuclear waste.

The highly publicized debates about nuclear reactors have tended to overshadow many other applications of nuclear reactions, such as the unique solutions for sensors and health care they can provide. As James Blanchard points out, alpha radiation sources could power devices implanted inside the body that could operate unattended for long periods of time with no risk of radiation damage. In the longer term, nuclear energy can also satisfy the propulsion requirements for long-duration space missions. Researchers are working to increase the practicality and efficiency of these technologies.

Quantum information technology is another area of research being vigorously pursued. Several presentations at the symposium focused on the implications of this technology for computational devices. As memory units in conventional computers approach the dimensions of an atom, their function will necessarily be determined by quantum mechanics (the quantum counterpart of the bit—the qubit—can be zero and one simultaneously). Quantum computers will require a new concept of computer architecture and new engineering; some intriguing experimental devices are already being developed. Bruce Kane assures us that quantum computer architecture will ultimately have as big an impact as the transistor and the integrated circuit.

Another speaker discussed quantum computing and cryptography. With current cryptographic methods, no matter how complex, the meaning of messages can almost always be decoded. Quantum computers, which will require unprecedented precision and complexity, will enable us to find and decode the meaning of messages and, at the same time, ensure the security of communications.

We have provided only a sampling of papers addressing these challenges and opportunities. To transform these possibilities into practical realities and to prepare our society for their implications, we will need a broad range of sustained research programs.

The end limit of Moore's Law scaling is the threshold of the quantum realm.

Scalable Quantum Computing Using Solid-State Devices

Bruce Kane

Bruce Kane is a member of the research staff in the Laboratory for Physical Sciences, University of Maryland, College Park.

The field of solid-state quantum computing is in its infancy. Coherent operations on single qubits (the simplest type of quantum logical operation) have only recently been demonstrated (Nakamura et al., 1999; Vion et al., 2002). Nevertheless, there is a great deal of optimism that solid-state implementations of quantum computers will ultimately lead to scalable architectures in the same way that the invention of the transistor and integrated circuit presaged the development of large-scale and networked conventional computers. The optimism is based on the tremendous amount of research being done over a broad front that is heading steadily toward the development of devices for conventional computation built on nearly the atomic scale. This limit is the end of Moore's Law scaling, but only the threshold of the quantum realm. Thus, the nascent field of solid-state quantum computing can capitalize on research intended for the development of smaller and faster conventional logical devices.

Many difficulties will have to be overcome before qubits can be integrated into solid-state systems. Because there are on the order of 10^{23} atoms in a solid-state device, it is very difficult to attain the decoupling from extraneous degrees of freedom that is necessary for large-scale quantum computing. Hence, much of the early research on solid-state quantum computing has been focused on identifying potential qubits inherently isolated from their surroundings. Most current research is focused either on superconducting qubits (quantum information is stored on flux states in a SQUID or on charge states of a small "Cooper pair box") or on electron-spin or nuclear-spin qubits in semiconductors. To have the necessary long decoherence times, these devices must invariably operate at low temperatures (< 1K). Even if research is successful, it is still not obvious that these technologies will be scalable (it is noteworthy that many conventional solid-state devices, such as bipolar transistors and tunnel diodes, proved to be unsuitable for very large-scale integrated circuits for reasons that only became apparent years after they were developed). Figure 1 shows the range of research being done on quantum computers.

A major surprise in the early days of quantum computing theory was that quantum error correction was possible at all; it has been shown that if a qubit of quantum information is redundantly coded into several qubits, errors in quantum computation can be reduced just as they can be corrected in classical communications channels (Neilson and Chuang, 2000). One certainty is that the operation of scalable quantum computers will rely heavily on error correction. There is a "threshold for error corrected continuous quantum computation." When errors at the single-qubit-level quantum operations are reduced below this threshold, quantum computation becomes possible.

The error threshold is still very stringent. At most, one error can occur in every ~10^4 operations. This level of accuracy is beyond the level of device variability of most, if not all, solid-state devices currently manufactured. Meeting the accuracy threshold will undoubtedly be one of the major challenges advocates for solid-state quantum computation will have to overcome. Even if the accuracy threshold can be reached, error correction will place a substantial overhead on the resources of a quantum computer because many physical qubits encode the same logical qubit. Also, most logical operations in the computer will simply be implementing error correction protocols (Steane, 2002).

Key Issues

Scaling of quantum computing will undoubtedly be a formidable task that justifies the skepticism expressed by many people (Keyes, 2001). Nevertheless, an outline of the leading issues can be helpful for a preliminary assessment of current approaches to large-scale quantum computing. Many of these issues relate to information *flow* rather than to individual quantum operations on which most current research is focused.

Efficient on-chip quantum communication will be essential for the development of large-scale solid-state quantum computing. Communication between devices is also important in conventional computers, but the need for quantum error correction necessitates the continuous transfer of redundant qubits throughout the computer. Rapid flow of quantum information will thus be essential for scalable quantum computing.

Cross talk must be minimized. As the number of qubits increases, the potential for errors due to unwanted coupling between qubits also increases. Spatially localized qubits could minimize this type of error.

Parallel logical and measurement operations must be

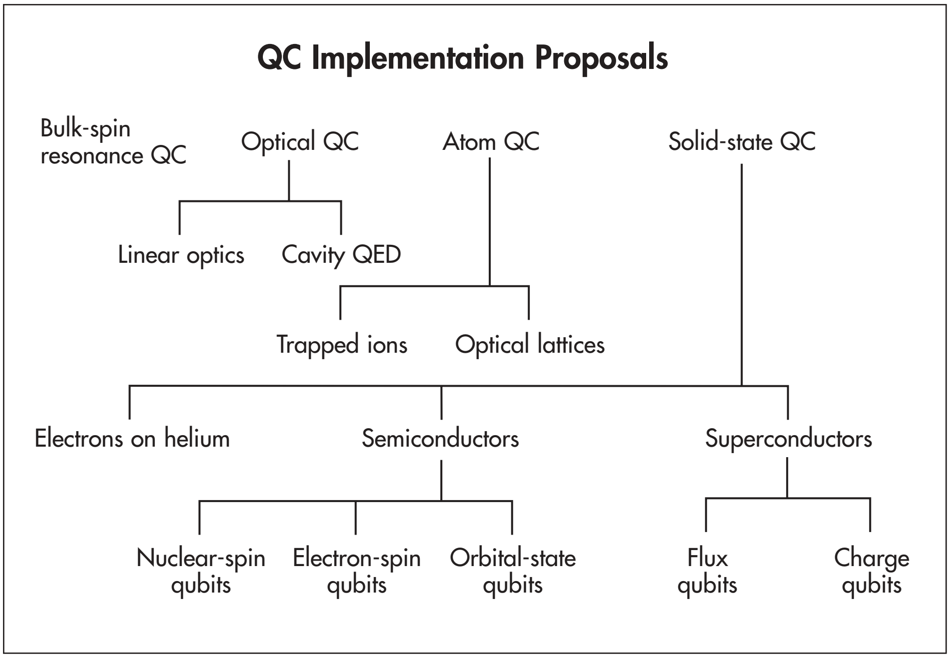

FIGURE 1 Diagram of the many possible realizations of quantum computers currently being explored experimentally. Bulk-spin resonance, optical, and atom-based qubits have all demonstrated elementary quantum logical operations, but solid-state implementations will particularly benefit from fabrication technologies being developed for conventional computer manufacturing. This synergy means that solid-state technologies are likely to be scalable and to benefit from continued advances in solid-state technology.

possible. We usually distinguish between the coherent logical operations of a quantum computer and the measurements of 0's and 1's that must ultimately produce the results of an algorithm. Error correction, however, requires that both types of operations go on together; in large-scale quantum computers they should occur simultaneously.

Logic, measurement, and communication must be able to be performed at high speed. Because of the exponential acceleration of quantum algorithms, a quantum computer operating at any clock speed will outperform its classical counterpart. However, given a choice between two otherwise equivalent quantum computer architectures, the faster architecture will be the most desirable.

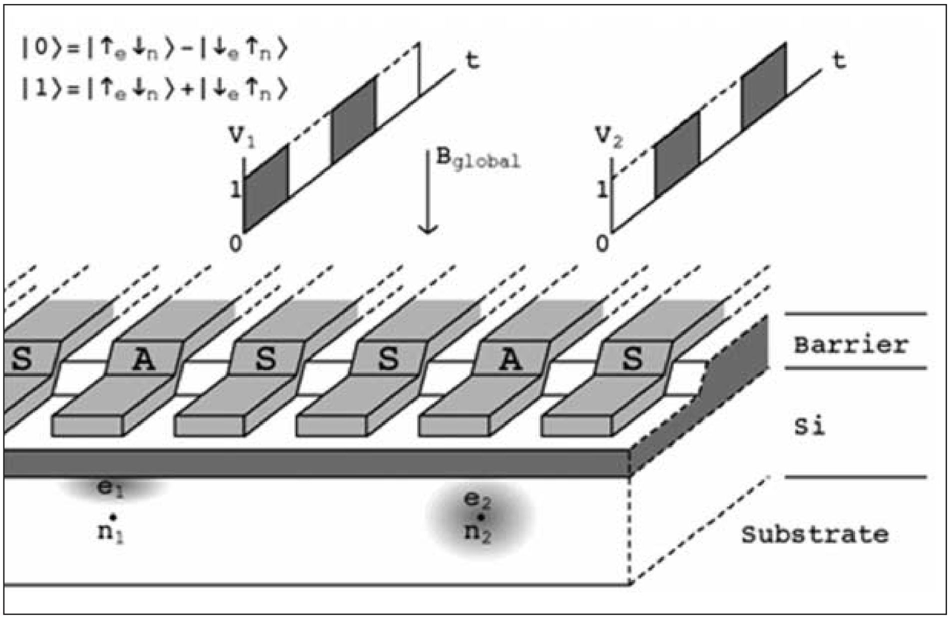

FIGURE 2 Diagram of a silicon-based quantum computer architecture. Single nuclear spins are the qubits; mobile electrons are used to manipulate the nuclear-spin states and move quantum information within the computer. Voltage pulses applied to metal gates on the top of the structure control the positions of electrons inside the silicon.

Individual quantum devices must be precisely engineered. The accuracy threshold for quantum computing suggests that the variability between quantum logical devices must differ by no more than 1 part in 10^4.

Major Limitations

As yet, no proposed implementation for large-scale quantum computers has addressed all of these criteria. However, it is possible to outline the major limitations of the approaches currently receiving the most attention.

Trapped-ion quantum computers. Although ion traps are not traditionally thought of as solid-state devices, recent proposals include complex metallizations on substrates to control and move ions between sites and are similar in many important ways to solid-state implementations. Kielpinski et al. (2002) have addressed many scaling issues, but moving ions to move quantum information is an intrinsically slow process because ion masses are typically 10^5 that of electrons. Therefore, it would be desirable if quantum information could be carried on lighter particles (like electrons).

Superconducting-qubit quantum computers. The primary advantage of superconducting qubits is that they are macroscopic. Consequently, devices are being fabricated with relatively simple micron-scale lithography. A drawback is that quantum information must be moved in the computer by electromagnetic excitations on metal traces. Large-scale implementations of superconducting quantum computers may thus be vulnerable to cross talk, a problem also encountered in conventional computers that have complex metal interconnects.

Electron-spin and nuclear-spin quantum computers. Quantum computer architectures that use electron spins or nuclear spins as qubits in a solid-state quantum computer are perhaps the most technologically challenging (Kane, 2000). These architectures also have some compelling advantages: spin qubits are known to be extremely well isolated from their environments in some materials and have longer quantum lifetimes (measured using electron-spin and nuclear-spin resonance techniques) than any other qubit under investigation in solids. Interestingly, silicon—the material in which almost all conventional computers are implemented—is also characterized by extremely long-lived spin states that can potentially be used for quantum computing. Spin coupling is extremely local, so cross talk is minimal if spins can be well isolated. Spin can be conveniently transported rapidly on electrons driven by electric fields (Skinner et al., 2002). Finally, parallel, rapid quantum logic and measurement appear to be possible using spin qubits (Figure 2).

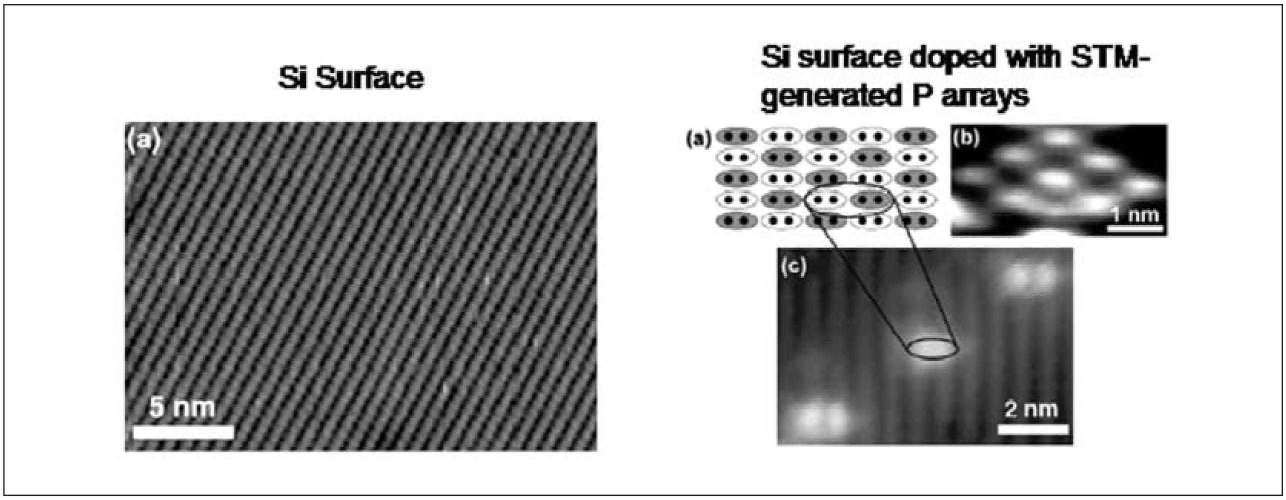

FIGURE 3 One possible route to the realization of single-spin quantum logical devices in silicon (Si) is via scanning tunneling microscope (STM) lithography. A single monolayer of hydrogen is formed on a pure Si surface (left). Using an STM, holes are punctured in the hydrogen; phosphorus is then introduced through the holes onto arrays in the Si crystal (right). Source: O'Brien et al., 2001. Reprinted with permission.

The major difficulty with spin-based implementations of quantum computers is that they require measurement and control of single electron spins or nuclear spins, a task that is only now on the threshold of realization. Scalable spin-based quantum computing will probably require the development of a new technology in which single atoms can be accurately positioned to create devices with the precision necessary for quantum computation. Fortunately, several promising approaches (Figure 3) for fabricating these single-atom devices are currently being explored (O'Brien et al., 2001).

Conclusion

The development of large-scale quantum computers will require an unprecedented combination of precision and complexity. Extremely complex conventional information processors are only possible because digital logic is tolerant to device variation. Quantum logic is much less forgiving. Thus, realizing the dream of a large-scale quantum computer will require that engineers overcome the daunting challenge of combining the precision of an atomic clock with the complexity of a modern microprocessor.

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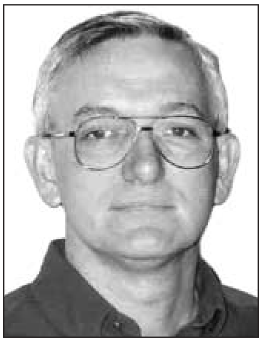
Computational fluid dynamics has enormous potential for industry in the twenty-first century.

The Role of Computational Fluid Dynamics in Process Industries

David Lee Davidson



David Lee Davidson, a fellow at Solutia, Inc., Pensacola, Florida, passed away on October 27, 2002. At Solutia, he was responsible for product and process development for fibers, polymers, and chemicals.

Continuum mechanics, one of our most successful physical theories, is readily applicable to the process industries. In continuum mechanics, the existence of molecules is ignored, and matter is treated as a continuous medium. The continuum hypothesis is valid, provided the equations of continuum mechanics are applied at sufficiently large length scales and time scales that the properties of individual molecules are not noticed. The mapping of the laws of mass, momentum, and energy conservation to the continuum results in field equations that describe the dynamics of the continuum. These field equations, variously known as the equations of motion, the equations of change, or simply the conservation equations, are nonlinear, partial differential equations that can be solved, in principle, when combined with the appropriate constitutive information[1] and boundary conditions.

Continuum mechanics is the mechanical analog of classical electrodynamics, in which a set of field equations (Maxwell's equations) describe the dynamics of the relevant variables of the electrical and magnetic fields. Whereas Maxwell's equations are linear *unless* the constitutive behavior is nonlinear, the equations of continuum mechanics are nonlinear, *regardless* of

[1] Examples of constitutive information are Newton's law of viscosity, which relates shear stress to shear rate, and Fourier's law of heat conduction, which relates heat flux to temperature gradient.

the constitutive behavior of the materials of interest. The inherent nonlinearity of the conservation equations, which is due to convective transport of momentum, energy, and chemical species, is responsible for certain fluid mechanical phenomena, such as turbulence, that have no electrodynamic analog and that complicate solution of the conservation equations.

Numerical solution of the equations of change has been an important research topic for decades.

Analytical solutions (e.g., obtained by eigenfunction expansion, Fourier transform, similarity transform, perturbation methods, and the solution of ordinary differential equations for one-dimensional problems) to the conservation equations are of great interest, of course, but they can be obtained only under restricted conditions. When the equations can be rendered linear (e.g., when transport of the conserved quantities of interest is dominated by diffusion rather than convection) analytical solutions are often possible, provided the geometry of the domain and the boundary conditions are not too complicated. When the equations are nonlinear, analytical solutions are sometimes possible, again provided the boundary conditions and geometry are relatively simple. Even when the problem is dominated by diffusive transport and the geometry and boundary conditions are simple, nonlinear constitutive behavior can eliminate the possibility of analytical solution.

Consequently, numerical solution of the equations of change has been an important research topic for many decades, both in solid mechanics and in fluid mechanics. Solid mechanics is significantly simpler than fluid mechanics because of the absence of the nonlinear convection term, and the finite element method has become the standard method. In fluid mechanics, however, the finite element method is primarily used for laminar flows, and other methods, such as the finite difference and finite volume methods, are used for both laminar and turbulent flows. The recently developed lattice-Boltzmann method is also being used, primarily in academic circles. All of these methods involve the approximation of the field equations defined over a continuous domain by discrete equations associated with a finite set of discrete points within the domain and specified by the user, directly or through an automated algorithm. Regardless of the method, the numerical solution of the conservation equations for fluid flow is known as computational fluid dynamics (CFD).

CFD was initially done without automation because the need to solve these equations (e.g., in aircraft design) preceded the development of electronic computers by several decades. With the advent of electronic computers, more ambitious numerical calculations became possible. Initially, CFD codes were written for specific problems. It was natural to generalize these codes somewhat, and eventually, particularly as computational resources became more readily available, general-purpose CFD codes were developed. It was then recognized that a business could be built upon the development and licensing of these codes to industrial, academic, and government users. Today, many of the general-purpose commercial codes are quite sophisticated, cost a tiny fraction of their development cost, and are probably the mainstay of the industrial application of CFD.

Four steps are required to apply a general-purpose CFD code to an industrial problem. First, the domain must be defined. This amounts to constructing the geometry for the problem,[2] which is typically done using a computer-assisted design (CAD)-like preprocessor.[3] Within the preprocessor, relevant physics are defined, appropriate models are specified, boundary and initial conditions are applied, and solver parameters are specified. Because the conservation and constitutive equations must be discretized on the specified geometry, the domain discretization must be specified. This process, known as meshing or grid generation, is the second step in the application of a CFD code to an industrial problem. Meshing can be accomplished using two basic protocols: (1) structured meshing, which involves creating an assembly of regular, usually hexahedral (quadrilateral in two dimensions) elements or control volumes throughout the domain; and (2) unstructured meshing, which involves filling the geometry with control

[2] Specification of the time dependence (transient or steady state) and certain boundary conditions (periodic, symmetry) are also required to specify the domain completely.

[3] The development of graphical user interfaces for commercial CFD codes in the last 10 to 15 years has significantly increased their accessibility.

volumes, often tetrahedrons and prisms, in an irregular fashion. Unstructured mesh generators are usually simpler to use with complicated geometries and involve some degree of automation. For example, the user may specify one or more measures of surface grid density, and the mesh generator will fill the volume with elements according to some algorithm. In the third step, the equations are discretized over the specified grid, and the resulting nonlinear[4] algebraic equations are solved. The development of solvers is still an active area of research, the goal being to improve the likelihood and rate of convergence. The fourth step, after satisfactory convergence is obtained, is to interrogate the solution to obtain the desired information. That information may be a single number extracted from the solution data set, an animation illustrating the transient macroscopic behavior of the entire flow field, or anything in between. Because the data sets can be quite large,[5] robust tools for data set interrogation are often required. These are usually provided with the commercial CFD codes, but one leading commercial tool is a stand-alone CFD post-processor (FIELDVIEW, 2002).

Current Industrial Applications

CFD is routinely used today in a wide variety of disciplines and industries, including aerospace, automotive, power generation, chemical manufacturing, polymer processing, petroleum exploration, medical research, meteorology, and astrophysics. The use of CFD in the process industries has led to reductions in the cost of product and process development and optimization activities (by reducing down time), reduced the need for physical experimentation, shortened time to market, improved design reliability, increased conversions and yields, and facilitated the resolution of environmental, health, and right-to-operate issues. It follows that the economic benefit of using CFD has been substantial, although detailed economic analyses are rarely reported. A case study of the economic benefit of the application of CFD in one chemical and engineered-material company over a six-year period conservatively estimated that the application of CFD generated approximately a six-fold return on the total investment in CFD (Davidson, 2001a).

CFD has an enormous potential impact on industry because the solution of the equations of motion provides everything that is meaningful to know about the domain. For example, chemical engineers commonly make assumptions about the fluid mechanics in process units and piping that lead to great simplifications in the equations of motion. An agitated chemical reactor may be designed on the assumption that the material in the vessel is perfectly mixed, when, in reality, it is probably not perfectly mixed. Consequently, the fluid mechanics may limit the reaction rather than the reaction kinetics, and the design may be inadequate. CFD allows one to simulate the reactor without making any assumptions about the macroscopic flow pattern and thus to design the vessel properly the first time. Similarly, the geometrically complicated parts required for melt spinning can be designed with CFD rather than rules-of-thumb or experiments, resulting in "right the first time" designs (Davidson, 2001b). Commercial publications (e.g., *CFX Update*, *Fluent News*, and *Applications from the Chemical Process Industry*) are filled with case studies illustrating how CFD was applied to the design of a particular unit, the optimization of a particular process, or the analysis of a particular phenomenon with good results.

The primary limitation is in the area of turbulent flow.

Areas of Research

There are, of course, limitations to the application of CFD, and active research is being done to overcome them. The primary limitation is in the area of turbulent flow. Turbulent flows are solutions to the equations of motion and can be computed directly, at least in principle. This approach, known as direct numerical simulation, requires a spatial grid fine enough to capture the smallest length scale of the turbulent fluid motion (the Kolmogorov scale) throughout the domain of interest and a correspondingly small time step. In typical problems of industrial interest, the ratio of the length scale of the domain to the Kolmogorov length scale is so large that the required grid is prohibitively large. Available

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4 The algebraic equations are linear if the associated partial differential equations are linear, for example when the constitutive behavior is linear and diffusion dominates.

5 Data sets of several hundred megabytes for industrial steady-state problems are not unusual, and many gigabytes are easily generated for typical transient problems.

computational resources are usually inadequate for this task except for relatively simple problems.

Consequently, industrial practitioners of CFD use turbulence models, usually by solving the Reynolds-averaged equations, that is, equations generated by averaging the equations of motion over a time scale that is much larger than the time scale of the turbulent fluctuations but much smaller than the smallest time scale of interest in the application. This procedure results in a set of equations that have the same form as the original equations of motion, but with time-averaged quantities in place of instantaneous quantities, plus one additional term that arises from the nonlinear convective terms in the original equations of motion. In the Reynolds-averaged momentum-conservation equation, for example, this additional term has the form of an additional stress, known as the Reynolds stress. This term is modeled based on the time-averaged quantities of the flow field. A variety of turbulence models are available (Wilcox, 1998), but the workhorse model of industrial CFD is the so-called k-epsilon model, which was introduced several decades ago (Casey and Wintergerste, 2000; Launder and Spalding, 1974). These turbulence models can lead to significant inaccuracies, and CFD practitioners must use them carefully.

The second limitation of CFD is for dispersed, multiphase flows.

Large eddy simulation (LES) is an alternative approach to turbulence modeling. Turbulent flows are characterized by an eddy cascade, in which large eddies transfer their kinetic energy to smaller eddies, which in turn transfer kinetic energy to even smaller eddies, and so on until, at the Kolmogorov scale, the kinetic energy is transformed into heat. LES attempts to solve for the larger eddies directly while modeling the smaller eddies. Although LES is more computationally intensive than other kinds of turbulence modeling, it has been applied to industrial-scale problems (Derksen, 2001).

The second great limitation of CFD is dispersed, multiphase flows. Multiphase flows are common in industry, and consequently their simulation is of great interest. Like turbulent flows, multiphase flows (which may also be turbulent in one or more phases) are solutions to the equations of motion, and direct numerical simulation has been applied to them (Miller and Bellan, 2000). However, practical multiphase flow problems require a modeling approach. The models, however, tend to ignore or at best simplify many of the important details of the flow, such as droplet or particle shape and their impact on interphase mass, energy, and momentum transport, the impact of deformation rate on droplet breakup and coalescence, and the formation of macroscopic structures within the dispersed phase (Sundaresan et al., 1998).

Enterprise-Wide Access

Although the commercial CFD industry has greatly simplified the use of CFD codes by providing CAD-like preprocessors, automatic mesh generation, graphical user interfaces for all aspects of model definition, and on-line documentation, the industrial practice of CFD is still primarily in the hands of specialists. Regular use of a general-purpose code requires significant expertise in transport phenomena, an understanding of the capabilities and limitations of the modeling approaches used to handle turbulence and dispersed multiphase flows, an understanding of the relationship between mesh quality, convergence, and solution accuracy, and proficiency with the various means of interacting with the CFD code, including the graphical user interface, advanced command languages (when available), and user-accessible FORTRAN subroutines.[6] For these reasons, attempts to train large numbers of engineers in the use of CFD have not been very successful (Davidson, 2001a). Nevertheless, the potential benefit of a much broader CFD user base is very great. In our opinion, CFD should be accessible to every person in the enterprise who makes decisions the outcomes of which are governed by the laws of physics, from the CEO who makes strategic business decisions based on business goals to the operator who adjusts valve positions to meet process goals.

We believe that this can be achieved through the development of so-called "digital experts," stand-alone CFD (and other) applications that would be integrated

[6] Although the graphical user interface (GUI) has greatly increased accessibility of the commercial codes, more experienced users sometimes avoid the use of the GUI altogether and rely on command languages, user FORTRAN, and ASCII files to integrate various tools and automate CFD tasks.

into commercial CFD codes (as appropriate) and wrapped in interfaces that speak the language of the industrial application, not the language of CFD. Digital experts would automate geometry construction, mesh generation, solver selection, and other processes behind the scenes. In addition, they would contain all of the algorithms necessary to nurse the CFD codes to solution automatically, without having to ask the user to define satisfactory convergence, for example. Finally, they would extract the essential ingredients from the complete CFD solution and present them to the user in a convenient and familiar format, so the user would not have to be concerned with interrogation of the flow field by computation or visualization. A discussion of one digital expert that has been developed for melt-fiber spinning has been published (Davidson, 2001b).

The decision to develop an industrial digital expert is based on the relationship between development cost and benefit. Recently, a commercial product has become available with the potential to change that relationship significantly. EASA™ (Enterprise Accessible Software Applications from AEA Technology), which was designed to help industrial practitioners develop digital experts, solves a number of problems for industrial developers, including construction of the graphical user interface, accessibility of the final product (the digital expert or *EASAp*) over the enterprise intranet, and the orchestration of computations on a heterogeneous computer network (Dewhurst, 2001). In essence, EASA allows an industrial CFD specialist to put bullet-proof digital experts in the hands of co-workers, with a consistent interface tailored to the user.

Summary

CFD is a powerful tool for solving a wide variety of industrial problems. Commercial general-purpose codes have the potential to solve a very broad spectrum of flow problems. Current research is concentrated on overcoming the principle weaknesses of CFD, namely how it deals with turbulence and dispersed multiphase flows. Development work on solver algorithms, meshing, and user interface generation are ongoing, with the objectives of improving accuracy, reducing solution time, and increasing accessibility. In spite of the limitations of CFD, the economic value of industrial applications has been demonstrated in a variety of industries, and its value as a research tool has been accepted in many areas, such as meteorology, medicine, and astrophysics. In industry, CFD is presently primarily in the hands of specialists, but the development of digital experts and tools to facilitate the development of digital experts may revolutionize the way industry uses CFD by providing ready access throughout the enterprise. This would result in significant gains in productivity and profitability.

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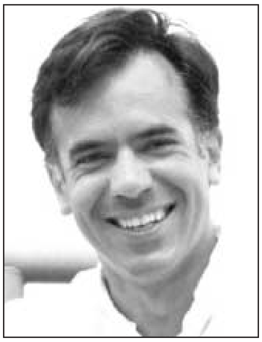
Most designers of technological systems do not pay enough attention to human needs and capabilities.

The Human Factor



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Kim J. Vicente

Many people find technology frustrating and difficult to use in everyday life. In the vast majority of cases, the problem is not that they are technological "dummies" but that the designers of technological systems did not pay sufficient attention to human needs and capabilities. The new BMW 7 series automobile, for example, has an electronic dashboard system, referred to as iDrive, that has between 700 and 800 features (Hopkins, 2001). An article in *Car and Driver* described it this way: "[it] may . . . go down as a lunatic attempt to replace intuitive controls with overwrought silicon, an electronic paper clip on a lease plan. One of our senior editors needed 10 minutes just to figure out how to start it" (Robinson, 2002). An editor at *Road & Track* agreed: "It reminds me of software designers who become so familiar with the workings of their products that they forget actual customers at some point will have to learn how to use them. Bottom line, this system forces the user to think way too much. A good system should do just the opposite" (Bornhop, 2002). As technologies become more complex and the pace of change increases, the situation is likely to get worse.

In everyday situations, overlooking human factors leads to errors, frustration, alienation from technology, and, eventually, a failure to exploit the potential of people and technology. In safety-critical systems, however, such as nuclear power plants, hospitals, and aviation, the consequences can threaten the quality of life of virtually everyone on the planet. In the

FIGURE 1 A typical control room for a nuclear power plant. Source: Photo courtesy of C.M. Burns.

United States, for example, preventable medical errors are the eighth leading cause of death; in hospitals alone, errors cause 44,000 to 98,000 deaths annually, and patient injuries cost between $17 billion and $29 billion annually (IOM, 1999).

Diagnosis

The root cause of the problem is the separation of the technical sciences from the human sciences. Engineers who have traditionally been trained to focus on technology often have neither the expertise nor the inclination to pay a great deal of attention to human capabilities and limitations. This one-sided view leads to a paradoxical situation. When engineers ignore what is known about the physical world and design a technology that fails, we blame them for professional negligence. When they ignore what is known about human nature and design a technology that fails, we typically blame users for being technologically incompetent. The remedy would be for engineers to begin with a human or social need (rather than a technological possibility) and to focus on the interactions between people and technology (rather than on the technology alone). Technological systems can be designed to match human nature at all scales—physical, psychological, team, organizational, and political (Vicente, in press).

Computer Displays For Nuclear Power Plants

People are very good at recognizing graphical patterns. Based on this knowledge, Beltracchi (1987) developed an innovative computer display for monitoring the safety of water-based nuclear power plants. To maintain a safety margin, operators must ensure that the water in the reactor core is in a liquid state. If the water begins to boil, as it did during the Three Mile Island accident, then the fuel can eventually melt, threatening public health and the environment. In traditional control rooms, such as the one shown in Figure 1, operators have to go through a tedious procedure involving steam tables and individual meter readings to monitor the thermodynamic status of the plant. This error-prone procedure requires that operators memorize or record numerical values, perform mental calculations, and execute several steps.

Beltracchi's display (Figure 2) is based on the temperature-entropy diagram found in thermodynamic textbooks. The saturation properties of water are shown in graphical form as a bell curve rather than in alphanumeric form as in a steam table. Furthermore, the thermodynamic state of the plant can be described as a Rankine cycle, which has a particular graphical form when plotted in temperature-entropy coordinates. By measuring the temperature and pressure at key locations in the plant, it is possible to obtain real-time sensor values that can be plotted in this graphical diagram. The saturation properties of water are presented in a visual form that matches the intrinsic human capability of recognizing graphical patterns easily and effec tively. An experimental evaluation of professional nuclear power plant operators showed that this new way of presenting information leads to better interactions between people and technology than the traditional way (Vicente et al., 1996).

Framework for Risk Management

Public policy decisions are necessarily made in a dynamic, even turbulent, social landscape that is continually changing. In the face of these perturbations, complex sociotechnical systems must be robust. Rasmussen (1997) developed an innovative framework for risk management to achieve this goal (Figure 3).

The first element of the framework is a structural hierarchy describing the individuals and organizations in the sociotechnical system. The number of levels and their labels can vary from industry to industry. Take, for example, a structural hierarchy for a nuclear power plant. The lowest level usually describes the behavior associated with the particular (potentially hazardous) process being controlled (e.g., the nuclear power plant). The next level describes the activities of the individual staff members who interact directly with the process being controlled (e.g., control room operators). The third level from the bottom describes the activities of management that supervises the staff. The next level up describes the activities of the company as a whole. The fifth level describes the activities of the regulators or associations responsible for setting limits to the activities of companies in that sector. The top level describes the activities of government (civil servants and elected officials) responsible for setting public policy.

Decisions at higher levels propagate down the hierarchy, and information about the current state of affairs propagates up the hierarchy. The interdependencies among the levels of the hierarchy are critical to the successful functioning of the system as a whole. If instructions from above are not formulated or not carried out, or if information from below is not collected or not conveyed, then the system may become unstable and start to lose control of the hazardous process it is intended to safeguard.

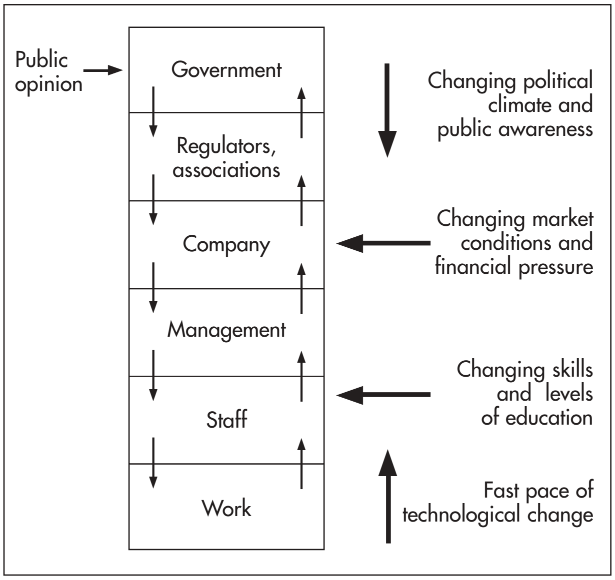

FIGURE 3 Levels of a complex sociotechnical system involved in risk management. Source: Adapted from Rasmussen, 1997.

In this framework, safety is an emergent property of a complex sociotechnical system. Safety is affected by the decisions of all of the actors—politicians, CEOs, managers, safety officers, and work planners—not just front-line workers. Threats to safety or accidents usually result from a loss of control caused by a lack of vertical integration (i.e., mismatches) among the levels of the entire system, rather than from deficiencies at any one level.

Inadequate vertical integration is frequently caused,

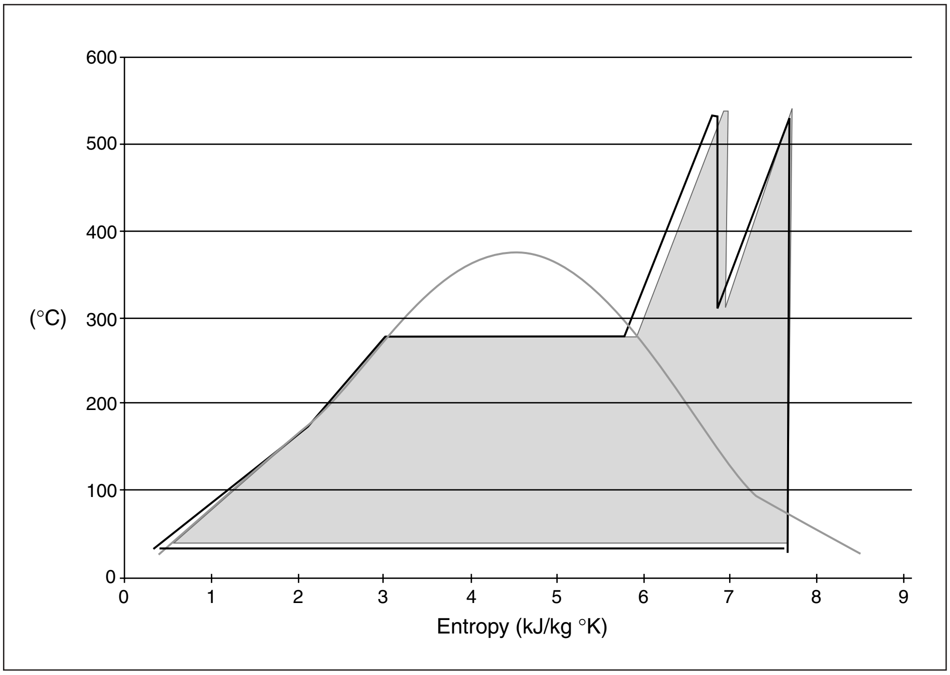

FIGURE 2 Beltracchi display. Source: Burns, 2000. Reprinted with permission.

at least partly, by a lack of feedback from one level to the next. Because actors at each level cannot see how their decisions interact with decisions made by actors at other levels, threats to safety may not be obvious before an accident occurs. Nobody has a global view of the entire system.

The layers of a complex sociotechnical system are increasingly subjected to external forces that stress the system. Examples of perturbations include: the changing political climate and public awareness; changing market conditions and financial pressures; changing competencies and levels of education; and changes in technological complexity. The more dynamic the society, the stronger these external forces are and the more frequently they change.

The second component of the framework deals with dynamic forces that can cause a complex sociotechnical system to modify its structure over time. On the one hand, financial pressures can create a cost gradient that pushes actors in the system to be more fiscally responsible. On the other hand, psychological pressures can create a gradient that pushes actors in the system to work more efficiently, mentally or physically.

Pressure from these two gradients subject work practices to a kind of "Brownian motion," an exploratory but systematic migration over time. Just as the force of gravity causes a stream of water to flow down crevices in a mountainside, financial and psychological forces inevitably cause people to find the most economical ways of performing their jobs. Moreover, in a complex sociotechnical system, changes in work practices can migrate from one level to another. Over time, this migration will cause people responding to requests or demands to deviate from accepted procedures and cut corners to be more cost-effective. As a result, over time the system's defenses are degraded and eroded.

A degradation in safety may not raise an immediate warning flag for two reasons. First, given the stresses on the system, the migration in work practices may be necessary to get the job done. That is why so-called "work-to-rule" campaigns requiring that people do their jobs strictly by the book usually cause complex socio-technical systems to come to a grinding halt. Second, the migration in work practices usually does not have immediate visible negative impacts. The safety threat is not obvious because violations of procedures do not lead immediately to catastrophe. At each level in the hierarchy, people may be working hard and striving to respond to cost-effectiveness measures; but they may not realize how their decisions interact with decisions made by actors at other levels of the system. Nevertheless, the sum total of these uncoordinated attempts at adapting to environmental stressors can slowly but surely "prepare the stage for an accident" (Rasmussen, 1997).

Migrations from official work practices can persist and evolve for years without any apparent breaches of safety until the safety threshold is reached and an accident happens. Afterward, workers are likely to wonder what happened because they had not done anything differently than they had in the recent past.

Rasmussen's framework makes it possible to manage risk by vertically integrating political, corporate, managerial, worker, and technical considerations into a single integrated system that can adapt to novelty and change.

Case Study

A fatal outbreak of *E. coli* in the public drinking water system in Walkerton, Ontario, during May 2000 illustrates the structural mechanisms at work in Rasmussen's framework (O'Connor, 2002). In a town of 4,800 residents, seven people died and an estimated 2,300 became sick. Some people, especially children, are expected to have lasting health effects. The total cost of the tragedy was estimated to be more than $64.5 million (Canadian).

In the aftermath of the outbreak, people were terrified of using tap water to satisfy their basic needs. People who were infected or who had lost loved ones suffered tremendous psychological trauma; their neighbors, friends, and families were terrorized by anxiety; and people throughout the province were worried about how the fatal event could have happened and whether it could happen again in their towns or cities. Attention-grabbing headlines continued unabated for months in newspapers, on radio, and on television. Eventually, the provincial government appointed an independent commission to conduct a public inquiry into the causes of the disaster and to make recommendations for change. Over the course of nine months, the commission held televised hearings, culminating in the politically devastating interrogation of the premier of Ontario. On January 14, 2002, the Walkerton Inquiry Commission delivered Part I of its report to the attorney general of the province of Ontario (O'Connor, 2002).

The sequence of events revealed a complex interaction among the various levels of a complex socio-technical system, including strictly physical factors, unsafe practices of individual workers, inadequate oversight and enforcement by local government and a provincial regulatory agency, and budget reductions imposed by the provincial government. In addition, the dynamic forces that led to the accident had been in place for some time—some going back 20 years—but feedback that might have revealed the safety implications of these forces was largely unavailable to the various actors in the system. These findings are consistent with Rasmussen's predictions and highlight the importance of vertical integration in a complex sociotechnical system.

Conclusions

We must begin to change our engineering curricula so that graduates understand the importance of designing technologies that work for people performing the full range of human activities, from physical to political activities and everything in between. Corporate design practices must also be modified to focus on producing technological systems that fulfill human needs as opposed to creating overly complex, technically sophisticated systems that are difficult for the average person to use. Finally, public policy decisions must be based on a firm understanding of the relationship between people and technology. One-sided approaches that focus on technology alone often exacerbate rather than solve pressing social problems.

Because the National Academy of Engineering has unparalleled prestige and expertise, it could play a unique role in encouraging educational, corporate, and governmental changes that could lead to the design of technological systems that put human factors where they belong—front and center.

Acknowledgments

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Fission power has the potential to provide a large fraction of the world's energy for centuries to come.

Sustainable Energy from Nuclear Fission Power

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Marvin L. Adams

Increases in world population and per-capita energy demand in the next few centuries are expected to cause a substantial rise in world energy use. The World Energy Council predicts a doubling of consumption to 800 EJ/yr (EJ = exaJoule = 10^{18} J) by 2050 (WEC, 2002). For energy production to be sustainable, input requirements (including construction materials) must be available at reasonable financial and environmental cost, and the waste stream must have acceptably low economic and environmental impacts. No production option has yet demonstrated the ability to meet a substantial fraction of projected demand sustainably: every option needs further research and development. In this paper, I summarize options for sustainable energy production, discuss the need for a significant contribution from nuclear fission and its potential for providing such a contribution, and identify some challenges that must be met to achieve that potential.

Options

In the following discussion of the relative merits of energy technologies hundreds of years into the future, we draw seemingly reasonable conclusions based on some fundamental truths. However, the possibility of unforeseen technological developments over such a long period of time introduces considerable uncertainty. With that caveat in mind, let us boldly proceed.

The vast majority of the world's energy in the coming centuries will come from a few sources: fossil fuels, the sun, biomass, wind, geothermal sources, nuclear fission, and (potentially) nuclear fusion. Table 1 provides an overview of the general suitability of each of these sources for sustainable energy production. Because the anticipated demand is high and because different technologies are better for different applications, it is likely that all of these sources will be tapped.

Economically recoverable oil and natural gas will probably be depleted within a century or two, and both have attractive applications besides energy production. Thus, I will not consider them as sustainable energy sources. The burning of coal produces a great deal of carbon dioxide (CO_2), a greenhouse gas. For coal to be a sustainable long-term energy option, either we must find a way to economically sequester the CO_2 (300 kg/s from each 1-GW_{el} power plant) or the world must decide that the addition of vast quantities of CO_2 to the atmosphere is environmentally acceptable. The burning of biomass also releases CO_2, but the same CO_2 is then captured by the growth of new matter. Thus, biomass does not add to atmospheric CO_2 levels. The greatest drawbacks of biomass are its large land use (according to the World Energy Council estimate, a sustainable 270 EJ/yr would require a crop area larger than the continental United States) and its high level of

TABLE 1 Comparison of Energy Sources

Source	EJ[a]/yr Today	Reserves[a]	Use of Other Resources	Waste	Comments
Oil/natural gas liquids[b]	140	> 6 ZJ		CO_2 and other emissions	Not considered sustainable.
Natural gas	85	> 5 ZJ		CO_2 and other emissions	Not considered sustainable.
Coal	90	30 ZJ	Land = moderate (mines) Construction = 0.7[c]	CO_2 and other emissions	Reserves greater than oil or gas, but much less than fission.
Biomass	55	Up to 270 EJ/yr sustainable	Land = high	Particulates and other emissions	R&D may help somewhat.
Nuclear fission	28	> 600 ZJ	Land = low Construction = 0.7	Long life Repository space Proliferation	Small waste volume. Space is political issue, not technical.
Hydroelectric power	9	30 EJ/yr sustainable	Land = high (lakes)		Inherently small role.
Solar energy	Small		Land = high Construction = 30–80		R&D may help somewhat.
Wind	Small		Land = high Construction = 5–15		Inherently diffuse source.
Geothermal energy	Small	<100 EJ/yr sustainable			
Nuclear fusion	0	Enormous			Not yet demonstrated.

[a] EJ = exaJoule = 10^{18} J; ZJ = zettaJoule = 10^{21} J.

[b] This does not include larger known reserves of oil shale, which is difficult and not cost effective to use with present methods.

[c] Construction number = approximate number of operation-months required to replace the energy used in construction; this is one measure of the intensity of use of other resources. Data from AWEA, 1998.

particulate and other emissions. Hydroelectric power is renewable and emission-free but limited to 30 EJ/yr, at most, by the availability of sites for dams. The sun seems to offer an almost limitless emission-free source of energy, and the role of solar power in the future energy supply will surely be significant, especially for small-scale local applications. However, solar energy is a diffuse source that requires large land areas, and its use of engineering materials is high per unit of energy produced. Technological advances will help, but the low energy density of solar radiation is a fundamental limitation that will be difficult to overcome for large-scale generation. Wind power is less material intensive than solar energy and will play an increasingly important role, but wind is also limited by its low energy density and relatively high land use. Other renewables, such as geothermal energy, have similar limitations. The technology for large-scale generation from nuclear fusion appears to be decades away, and its costs are uncertain. Although fusion has enormous potential, it is not yet clear how its advantages and disadvantages will compare to those of other options, including nuclear fission.

Each of these options has drawbacks, and each has positive features. Most of the drawbacks of any option can be overcome if we are willing to pay enough (in dollars, land, materials, etc.). It is reasonable to conclude that we should continue to develop all options and that all of them will be needed to some extent to meet the energy demand in the coming centuries.

Fission power uses little land and requires modest construction inputs per unit of energy produced.

Sustainable Fission Energy

The known economically recoverable 3.3 million metric tons of uranium (WEC, 2001) and 4 to 6 million metric tons of thorium (UNDP, 2000) could produce 250 ZJ (zettaJoule) and 350 to 500 ZJ, respectively, if used to their full potential. Thus, more than 600 ZJ of potential nuclear fission energy—1,500 times the current total worldwide annual energy consumption—is readily available. Much more easily recoverable thorium will surely be found if a demand develops (Rubbia et al., 1995). An additional 7 million metric tons of uranium is estimated but not yet proven to be economically recoverable (WEC, 2001). Fission power uses little land and requires modest construction inputs (mainly concrete and steel) per unit of energy produced—lower than the construction inputs for wind and solar energy by factors of 10 and 100, respectively (AWE, 1998). Thus, as far as inputs are concerned, fission power has the potential to provide a large fraction of the world's energy for many, many centuries. However, tapping the full potential energy of uranium and thorium resources will require changes from current fission-energy practice, including the use of "high-conversion" reactors and the recycling of fissionable isotopes.

The output from fission power includes modest amounts of chemical and low-level radioactive wastes, which are relatively easy to handle, as well as used ("spent") fuel, which is the main disposition challenge. Spent fuel from today's power reactors contains approximately 5 percent fission products (atoms produced by splitting another atom or by radioactive decay of another fission product), 2 percent "fissile" material (including ^{235}U, ^{239}Pu, and ^{241}Pu), and 1 percent other actinides (including ^{238}Pu and ^{241}Am), with ^{238}U comprising most of the remaining mass. ("Fissile" means the atom is likely to fission after absorbing any neutron, including a low-energy neutron.) Note that fission power produces a very small volume of spent fuel. With current technology, six years of operation of a 1-GW_{el} plant yields spent fuel that could fit inside a 4-meter cube, and the vast majority of this material is recyclable. If we recycle, which is essential for the substantial use of uranium and thorium resources, then much less material will require disposal, and most of it will have a much shorter half-life.

Tapping the Energy

In the current "once-through" fission fuel cycle in the United States, uranium fuel that is enriched to 3 to 5 percent in the ^{235}U isotope remains in a power reactor for four to six years, after which it is treated as waste. In the enrichment process, each kilogram (kg) of natural uranium (which is 0.7 percent ^{235}U) is typically converted to 0.85 kg of "depleted" uranium (0.2 percent ^{235}U) and 0.15 kg of low-enriched uranium (3.5 percent ^{235}U). Thus, only 15 percent of the mined uranium reaches a reactor. During its four to six years in the reactor, approximately 5 percent of the atoms in the uranium fuel fission. Thus, current practice releases only 0.75 percent (5 percent of 15 percent) of the potential energy of the mined uranium; a great deal of the energy-storing material is treated as waste.

Essentially all natural thorium is ^{232}Th, and 99.3 percent of natural uranium is ^{238}U. These isotopes are not fissile—they do not fission when they absorb low-energy neutrons—and neither can fuel a reactor by itself. Both are fissionable (absorption of MeV-range neutron can cause fission) and fertile (capture of a neutron leads to a new fissile atom). To unlock the energy from uranium and thorium resources, the abundant fertile isotopes (^{238}U and ^{232}Th) must be converted into fissile isotopes (^{239}Pu and ^{233}U, respectively). This is simple: if either ^{238}U or ^{232}Th captures a neutron, it quickly converts via beta decay:

(1)

$$^{238}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{239}_{92}\mathrm{U} \xrightarrow[23\ \mathrm{min}]{\beta^-} ^{239}_{93}\mathrm{Np} \xrightarrow[2.3\ \mathrm{days}]{\beta^-} ^{239}_{94}\mathrm{Pu}$$

(2)

$$^{232}_{90}\mathrm{Th} + ^{1}_{0}\mathrm{n} \rightarrow ^{233}_{90}\mathrm{Th} \xrightarrow[22\ \mathrm{min}]{\beta^-} ^{233}_{91}\mathrm{Pa} \xrightarrow[27\ \mathrm{days}]{\beta^-} ^{233}_{92}\mathrm{U}$$

The conversion ratio of a reactor is the production rate of fissile atoms (by conversion of fertile atoms) divided by the consumption rate of fissile atoms (by fission or other neutron-induced destruction). A reactor with a conversion ratio greater than unity is sometimes called a breeder reactor. Unlocking all of the potential energy in ^{238}U and ^{232}Th will require high-conversion reactors.

High-conversion reactors have been demonstrated for both ^{239}Pu/^{238}U and ^{233}U/^{238}Th cycles; however, this technology is not as mature as the technology used in current commercial reactors. There are opportunities for innovation in many aspects of the design of high-conversion reactors, including materials (for higher temperature operation and improved resistance to corrosion and radiation damage), fuel form (e.g., oxide, metal, molten salt), and coolant (e.g., liquid metals, helium). Innovations will undoubtedly improve the technology, but even today it is clear that high-conversion reactors can be designed and operated for sustainable fission power.

To take advantage of high-conversion reactors that convert fertile material to fissile material, we must recycle the new fissile material into new fuel. In fact, to maximize the energy and minimize the waste from uranium and thorium, all actinides (not just fissile isotopes) should be recycled so that as many heavy atoms as possible can fission. This will require reprocessing spent fuel, separating out the desired elements, and using reactors that can cause most of the actinides to fission. Reprocessing is a commercial practice in England and France, as is highly efficient (> 99.8 percent) extraction of uranium and plutonium. Efficient extraction of other actinides has been demonstrated on a laboratory scale, and research and development are under way to improve these technologies and move them to commercial scale.

Because of the mix of fissile and fissionable isotopes that develops after several recycling steps, fuel from multiple recycling steps is best suited for fast-spectrum reactors. In a fast-spectrum reactor, neutrons retain relatively high energy from birth (via fission) to death (via absorption or escape). Fast-spectrum reactors can cause nonfissile actinides to fission, whereas other reactors have trouble doing so. High-conversion reactors can be fast-spectrum reactors, and thus could be both creators of fissile material and burners of nonfissile actinides.

Handling the Waste

If a substantial majority of the actinides are recycled and made to fission in fast-spectrum reactors, the remaining waste will be mainly fission products. Most fission products decay with half-lives of decades or shorter, and after 300 years the total fission-product inventory decays to a radiotoxicity level lower than that of the original ore (OECD, 1999). Fission products can be immobilized in glass; this is done commercially in England and France. The waste-containing borosilicate glass is so insoluble that if it were immersed in water, only 0.1 percent would dissolve in 10,000 years. Thus, it is not difficult to immobilize fission products for several hundred years, after which they are no more harmful than the original ore that nature placed underground. The waste-containing glass can be isolated, for example, in stable underground geologic formations.

If we wanted to reduce the radiotoxicity of fission products even further, we would need to address the fission products with long half-lives. The fission products that contribute most to long-term radiotoxicity are ^{99}Tc and ^{129}I, which have half-lives of 2.1×10^5 and 1.6×10^7 years, respectively. These isotopes could conceivably be separated from other fission products and transmuted (by absorption of neutrons from accelerators, reactors, or accelerator-driven subcritical assemblies) into shorter-lived isotopes (NRC, 1996; OECD, 2002). A recent study concludes that both of these isotopes could be transmuted so that their products would decay with 51-year half-lives (OECD, 2002). This would eliminate them as potential long-term hazards.

No separation technology is 100 percent efficient; thus, even with actinide recycling, some fraction of the actinides will remain with the fission products for disposal. The efficiency of the separations will determine the long-term (>1,000 years) radiotoxicity of the waste from fission power. For example, if 99.9 percent of the plutonium and 99 percent of the americium (Am), curium (Cm), and neptunium (Np) were separated, with all other actinides remaining with the waste, then it would take 10,000 years for radiotoxicity to decay to ore levels—a substantial increase over the 300 years required if 100 percent of all actinides were separated out (OECD, 1999). Increasing the separation efficiency to 99.9 percent of Am, Cm, and Np would reduce this to less than 1,000 years. Thus, the efficiency of separation of actinides has a significant impact on the waste-isolation time and thus on the difficulty of the waste-isolation problem. Economical separation of >99.8 percent of plutonium has been demonstrated on a commercial scale (COGEMA's La Hague plant), and 99.9 percent separation of Am has been demonstrated on a laboratory scale. Research and development continues to improve the technology for actinide separation; thus, it seems reasonable to expect that highly efficient (≈99.9 percent) separation of key actinides will be economically achievable eventually. This raises the possibility of a relatively short waste-isolation time (a few hundred years), which would greatly simplify waste disposal.

The recycling of actinides would greatly simplify waste disposal.

The $^{233}U/^{232}Th$ cycle creates fewer transuranic atoms per unit of energy produced and, thus, in some sense creates less of a long-term waste problem (Rubbia et al., 1995). However, it also makes recycling somewhat more difficult, largely because the daughters of the recycled ^{233}U are more highly radioactive than ^{239}Pu and its daughters, which means hands-on operations must be replaced by remote-controlled operations.

In summary, if a substantial majority of actinides are recycled (which will be necessary for us to tap the majority of the potential energy of uranium and thorium resources), then the waste stream from fission power will consist of a very small volume of fission products along with a small fraction of lost actinides. This waste can be readily immobilized in an insoluble material, such as borosilicate glass. The efficiency of actinide-separation technology will determine whether this waste inventory will decay to ore-level radiotoxicity in hundreds of years or thousands of years. Thus, improvements in separation technology may have a significant impact on the waste-isolation time and on public acceptance of fission power.

One disadvantage of actinide recycling is that recycled fuel costs approximately 10 to 20 percent more than fresh fuel. Another is that recycling technology could conceivably enable countries or groups to develop nuclear weapons—the proliferation issue.

Proliferation

Nuclear weapons use highly concentrated fissile material, such as uranium that is highly enriched in ^{235}U or plutonium that is mostly ^{239}Pu. Highly enriched ^{235}U can be obtained by the same process that produces low-enriched ^{235}U for reactor fuel—the process is simply carried farther. (This is the process North Korea recently acknowledged using in its weapons program.) ^{239}Pu is generated in every reactor that contains ^{238}U (see Eq. (1)); however, if fuel stays in a reactor for more than a few months, significant quantities of other plutonium isotopes are also created, which makes the plutonium more difficult to use for weapon design and fabrication. Nevertheless, a National Research Council report has concluded that a credible weapon could be made from plutonium of almost any isotopic composition (NRC, 1995).

The $^{232}Th/^{233}U$ cycle may be more proliferation-resistant than the $^{238}U/^{239}Pu$ cycle, because ^{233}U daughter products generate heat and radiation that could make it difficult to design, build, and maintain weapons. Nevertheless, it is technically possible to create weapons from separated ^{233}U.

Every country that has developed nuclear weapons has obtained its concentrated fissile material from dedicated military programs, not by co-opting power-reactor technology. Nevertheless, there is a concern that if recycling technology is developed and widely used in the power industry, it could be used by some nations or groups to produce plutonium for a weapons program. A challenge, therefore, is to develop an economical, practical, proliferation-resistant fission-fuel cycle. This is one goal of the Generation-IV Reactor Development Program (Kotek, in press). One example of a proliferation-resistant technology that includes recycling of valuable actinides is the integral fast-reactor concept (Till et al., 1997). With this technology, Pu is never separated from U during reprocessing, and thus no weapons-usable material ever exists at any stage of the process.

Near-Term Issues

Achieving sustainable fission energy will require changes in current practices, especially in the United States. Current U.S. policy is for all spent fuel to be shipped to a geologic repository (recently identified as Yucca Mountain, Nevada) with no reprocessing. This is a once-through, or "open," fuel cycle. There are several adverse consequences of not reprocessing spent fuel:

1. More than 99 percent of the potential energy in the uranium is lost.
2. Some actinides have long half-lives (24,000 years for ^{239}Pu), which leads to stringent long-term requirements for disposal technologies.
3. Some actinides generate heat, which limits repository capacity.

The first consequence is significant for the very long term. The second affects public acceptance of nuclear power and public acceptance of any given repository site (people wonder how anyone can know that the material will remain sufficiently isolated for tens of thousands of years) and poses significant technical challenges. The third affects the capacity of a given repository. The latter two effects are very important for the near term (i.e., the next few decades).

From a technical point of view, repository space is not an issue. There appear to be more than enough suitable stable geologic formations in the world to handle waste from millennia of fission reactors, especially if fissionable materials (actinides) are recycled. However, because of the political picture today, repository space is a precious commodity. After 20 years of study, more than $4 billion of expenditures, and several political battles, the Yucca Mountain site has very recently been selected by the U.S. Department of Energy and Congress as the repository location for which the DOE will attempt to obtain a license. If licensing proceeds as quickly as possible, the first spent fuel will not be delivered until 2010 or later. Given the current once-through, no-reprocessing fuel strategy, the current U.S. fleet of reactors will produce enough spent fuel by 2040 to fill the Yucca Mountain repository to its estimated technical capacity (DOE, 2002). The addition of new reactors would of course hasten this date. Clearly, in the near term in the United States, repository capacity must be increased for fission power to achieve its potential. It seems equally clear that finding a second repository site would be challenging, especially politically.

The capacity of Yucca Mountain is limited by the thermal load it can accommodate.

The capacity of Yucca Mountain is limited by the thermal load it can accommodate (radioactive decay releases energy that heats the material). If the waste produced lower W/kg, more mass could be accommodated (DOE, 2002). With the current once-through fuel strategy, the main thermal load after a few decades will come from the decay of the isotopes ^{238}Pu and ^{241}Am, with half-lives of 88 and 432 years, respectively. If plutonium and americium were removed from the spent fuel, the heat load would be dominated by isotopes with 30-year half-lives; thus, the thermal load of a given mass of spent fuel would be halved every 30 years (P.F. Peterson, University of California-Berkeley, personal communication, June 2002). In other words, half of the repository capacity would effectively be regenerated every 30 years. It is easy to imagine that this might be more achievable politically than obtaining approval for another repository site.

Summary and Conclusions

Worldwide energy use is likely to increase in the foreseeable future, and sustainable energy sources are not abundant. It seems likely that many different sources will be tapped to meet energy needs. Nuclear fission could potentially provide a significant fraction of the world's energy for millennia: its inputs (fuel and construction materials) are readily available and its waste stream (fission products and lost actinides) is very small and not technically difficult to handle. Realizing the potential of fission energy will require high-conversion reactors and the recycling of fissionable atoms, which in turn will require that some technical and political challenges be met.

In the short term, especially in the United States, waste-repository capacity is a significant issue. The long-term capacity of the Yucca Mountain repository could be increased significantly by separating plutonium and americium from spent reactor fuel.

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Radioisotopes are being used in numerous commercial applications, and many more are on the horizon.

Stretching the Boundaries of Nuclear Technology

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Most people are well aware that nuclear power can be used to produce electricity, but few are aware that it can be used to provide power in many other situations. Radioisotopes have been used for decades in commercial applications, such as pacemakers and smoke detectors, and recent trends indicate that other applications are on the horizon. Two technologies being actively investigated are space nuclear power and nuclear energy for microelectromechanical systems (MEMS).

Space Nuclear Power

In 1989, a national space policy was approved that included the goal of putting a person on Mars by 2019. By most accounts, meeting this goal will require nuclear propulsion in order to shorten the mission time, thereby reducing exposure to zero gravity conditions and cosmic rays. Hence, nuclear propulsion will play a major role in space travel beyond the moon. This year, NASA announced a five-year, $1-billion program to develop nuclear reactors to power the next generation of spacecraft.

History

Early work on nuclear propulsion was primarily focused on nuclear-thermal technologies, in which a fission reactor is used to heat a gas and accelerate it through a nozzle. Research activity in this area began in 1944 and peaked in the 1960s. A typical design uses hydrogen as a propellant and graphite-moderated carbide fuel in the reactor core. One design, called Phoebus, achieved 5,000 MW of thermal power and 1 MN of thrust, which is about half the thrust of a space-shuttle engine (Bower et al., 2002).

Another early concept for nuclear propulsion was Project Orion, which relied on a series of nuclear blasts behind the payload to create shock waves that accelerated the device (Schmidt et al., 2002). Although this technology looked promising, it was abandoned in the 1960s because of a ban on nuclear testing.

Fuel Efficiency and Mission Length

The efficiency of the fuel used for propulsion is measured by a parameter called the specific impulse, which is defined as the ratio of the thrust produced to the rate at which fuel is consumed. The units of this parameter, typically seconds, are determined by dividing force by weight of fuel consumed per unit time. Hence, a specific impulse of N seconds can be interpreted as a capability for providing a unit thrust with a unit weight of fuel for N seconds. By comparing the specific impulses for different propulsion technologies, one can assess their advantages and disadvantages. Increased fuel efficiency is manifested in several ways—shorter trips, larger payloads for a fixed total launch weight, and flexibility for scientific activities at the destination.

The specific impulses for several propulsion options are shown in Table 1. The specific impulse for nuclear fuels can be many times that of chemical fuels, while the thrust is correspondingly lower and the run time longer. Electrostatic thrusters have relatively low thrust but can run virtually continuously and, therefore, can provide short trip times and low launch weights for a given payload. In contrast, chemical rockets tend to run at high thrust for short times, accelerating rapidly as the rocket fires and then coasting between necessary adjustments in trajectory.

Nuclear-Electric Propulsion

There are three basic types of electric propulsion systems: electrothermal, electrostatic, and electromagnetic. In electrothermal propulsion, the propellant is heated either by an electric arc or a resistance heater. The hot propellant is then exhausted through a conventional rocket nozzle to produce thrust. Electrostatic propulsion uses electric fields to accelerate charged particles through a nozzle. In electromagnetic propulsion, an ionized plasma is accelerated by magnetic fields. In all three types, electricity from a nuclear source, such as a fission reactor, is used to power the propulsion device (Allen et al., 2000; Bennett et al., 1994). The power flow for a typical nuclear-electric propulsion scheme is shown in Figure 1.

The most mature of the electric propulsion concepts is electrostatic propulsion. NASA's Deep Space 1 device (Figure 2), launched in 1998, relies on an ionized xenon gas jet for propulsion (Brophy, 2002). The xenon fuel fills a chamber ringed with magnets, which control the flow; electrons emitted from a cathode ionize the gas. The ions pass through a pair of metal grids at a potential of 1,280 volts and are thus accelerated out the back. A second electrode emits electrons to neutralize the charge on the device. The engine is capable of producing 90 mN of thrust while consuming 2,300 W of electrical power. This device is solar powered, but future designs anticipate using a fission reactor to produce the electricity.

All electric propulsion systems require supplies of electricity, and fission reactors, which have high power density, are an excellent choice for meeting this need. Numerous projects are under way to develop fission reactors with low weight, high reliability, long life without refueling, and safety during launch. A wide variety of heat-transport and energy-conversion technologies are being investigated. One example of a fission reactor is

TABLE 1 Propulsion Parameters for Several Propulsion Technologies

Technology	Specific Impulse (sec)	Thrust per Engine (N)	Run Time (duration)
Chemical	150–450	0.5–5 million	A few seconds to hundreds of minutes.
Nuclear thermal	825–925	5,000–50,000	A few minutes to several hours.
Electromagnetic	2,000–5,000	10–200	A few seconds to several hundred hours.
Electrostatic	3,500–10,000	1–10	A few minutes to several days or months.

Source: Niehoff and Hoffman, 1996. Reprinted with permission of the American Astronautical Society.

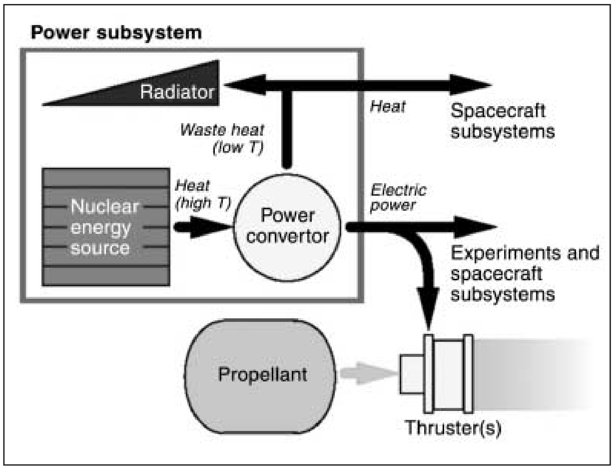


FIGURE 1 Schematic drawing of power flow for a typical nuclear-electric propulsion device. Heat is produced in the nuclear source (typically a fission reactor core) and converted to electricity in the power converter. The electricity is then used to power the thruster. The radiator dissipates the waste heat. Source: NASA, 2001.

the safe, affordable fission engine (SAFE-400), a 400-kW (thermal) reactor that is expected to produce 100 kW of electric power using heat pipes for energy transport and a Brayton cycle for energy conversion (Poston et al., 2002). The core consists of 381 uranium-nitride fuel pins clad with rhenium. The uranium-nitride fuel was chosen because of its high uranium density and high thermal conductivity. Molybdenum/sodium heat pipes are used for heat transport to provide passive safety features in case of an accident.

Plasma Propulsion

An approach related to electric propulsion is the plasma rocket, exemplified by the variable specific impulse magnetoplasma rocket (VASIMR) (Diaz, 2000). Like an ion thruster, a VASIMR injects a propellant (usually hydrogen) into a cell and ionizes it. The resulting plasma is heated using radio-frequency injection and a magnetic nozzle that accelerates the gas to provide the propulsion. A second example is the gas dynamic mirror, a long, slender device in a magnetic mirror configuration. This device is powered by fusion reactions in the plasma; the thrust is produced by plasma ions exiting the end of the device. Accelerated by the mirror's magnetic-field gradients, the ions provide efficient propulsion. One concept features a 50 m long, 7 cm radius plasma and produces 50,000 N of thrust at a specific impulse of more than 100,000 seconds (Kammash et al., 1995).

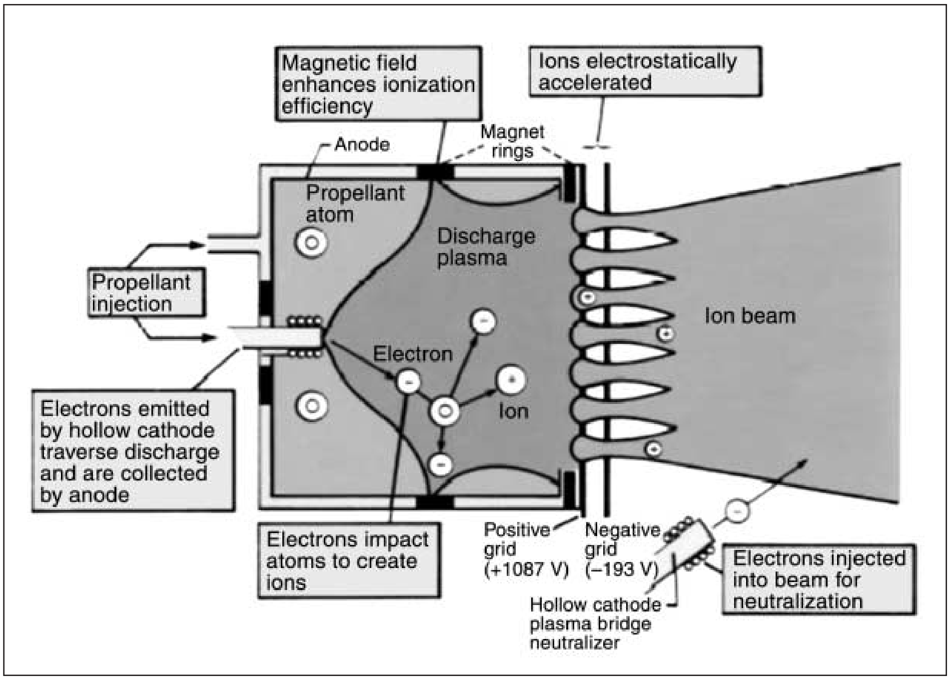
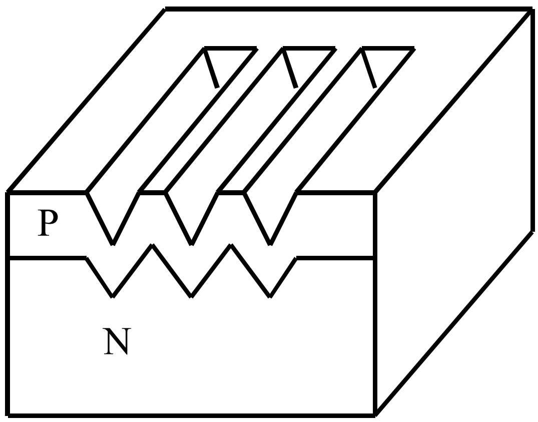


FIGURE 2 Schematic drawing of the Deep Space 1 ion thruster. Source: NASA, 2002.

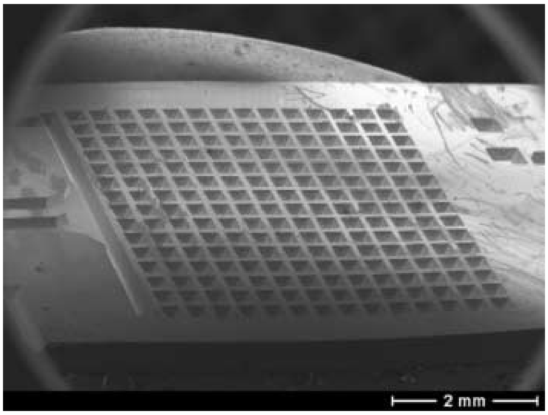
Small-Scale Radioisotope Power

MEMS have the potential to revolutionize many technologies, and the number of commercial applications is increasing rapidly. Many applications, such as pumps, motors, and actuators, can be improved with onboard power supplies, and various technologies are being explored to provide such power. Obvious choices, such as chemical batteries, fuel cells, and fossil fuels, show some promise, but none of them can match radioisotope power for long, unattended operation (Blanchard et al., 2001). This is because of the larger energy density available with nuclear sources.

Radioisotopes can be used to produce power in a variety of ways. Thermoelectric and thermionic technologies convert the heat generated by the decay to electricity; other approaches make more direct use of the released energy. Thermoelectric conversion uses a thermal gradient between two different materials to



3a



3b

FIGURE 3a A schematic drawing of a simple device using a P-N junction and radioactive source to produce the potential. FIGURE 3b Photograph of a device using pits rather than trenches to hold the source.

create a current via the Seebeck effect. Thermionic conversion creates a current by boiling electrons off a cathode (at high temperature) and catching them at an anode. Techniques for more direct methods include simple collection of the emitted charged particles, ionization near a P-N or P-I-N junction in a semiconductor, and conversion of the decay energy to light and subsequent conversion to electricity in a photovoltaic.

History

Radioisotopes have been used as power sources for decades. Early pacemakers were powered by approximately 0.2 grams (3 Ci) of ^{238}Pu, producing about 0.2 mW and delivering about 0.05 mW to the heart muscle (Parsonnet, 1972). Whereas pacemakers powered by chemical batteries have lives of less than 10 years and thus require replacement in most patients, the half-life of ^{238}Pu (approximately 86 years) permits radioisotope-powered devices to last the life of the patient.

Although a smoke detector is not strictly a power source, many smoke detectors contain radioisotopes (usually 1 to 5 microcuries of ^{241}Am). The source ionizes air between a pair of parallel plates, and a chemical battery (or house current) is used to collect these charges and thus measure the degree of ionization in the gap. When smoke enters the gap, the increased ionization trips the sensor.

Radioisotope thermoelectric generators (RTGs) are used in many applications, including underwater power and lighting in remote locations, such as the Arctic (Lange and Mastal, 1994). RTGs were also used to provide power for the Cassini and Voyager missions. Much like the pacemakers mentioned above, RTGs create power by thermoelectric conversion. Most RTGs are modular, with each module containing approximately 2.7 kg of Pu (133 kCi) and measuring approximately 42 cm in length and 114 cm in diameter. The modules produce 276 W of electric power at the beginning of life and, despite decay of the isotope, will produce approximately 216 W after 11 years of unattended operation.

Current research is focused mostly on the miniaturization of RTGs for many applications, such as MEMS; in addition, efforts to improve the efficiency of existing RTGs are ongoing.

Nuclear Microbatteries

Thermal devices, such as RTGs, are difficult to reduce to the microscale because, as the size is decreased, the surface-to-volume ratio increases, thus increasing the relative heat losses and decreasing the efficiency of the device. Hence, microbattery designs have tended to focus on direct methods of energy conversion. For example, one can construct a diode from silicon using a layer of P-type silicon adjacent to a layer of N-type silicon and a radioactive source placed on the top of the device. As the source decays, the energetic particles penetrate the surface and create electron-hole pairs in the vicinity of the P-N junction. This creates a potential across the junction, thus forming a battery. Figure 3a is a schematic drawing of such a device, and Figure 3b is a photograph of one concept created at the University of

Wisconsin. The device shown in Figure 3b is fairly large, measuring approximately 0.5 cm on each side, but one can easily imagine using a single pit from the device as a power source. This would provide a microbattery measuring approximately 400 microns by 400 microns by 50 microns; using a beta emitter (^{63}Ni), it could produce approximately 0.2 μW of electrical power. An early prototype of the device pictured in Figure 3b, loaded with a weak source (64 microcuries of ^{63}Ni), produced approximately 0.07 nW of power. Given that the thermal energy of 64 microcuries of ^{63}Ni is 6.4 nW, this device is about 1 percent efficient. Placing a second diode on top of the source would nearly double the efficiency (because the decay products are produced isotropically). Work is also under way to improve the efficiency by optimizing the design.

When an alpha source is used in such a battery, the available energy for a fixed activity level is increased by several orders of magnitude. Unfortunately, the high-energy alpha particles damage the silicon lattice as they pass through and quickly degrade the power. Attempts are being made to overcome this limitation by using materials that are resistant to damage. Materials being considered include wide-band-gap semiconductors, such as gallium nitride, which might improve radiation stability and device efficiency (Bower et al., 2002).

Thermoelectric devices are another approach to using alpha sources. These devices use the heat from the source to produce a temperature gradient across the thermoelectric device to produce power. Thus, there is no risk of radiation damage, and alpha particles could be used. Hi-Z Technology, Inc. (San Diego), developed a 40 mW device using a radioisotope heater unit (RHU) that was produced by NASA several years ago. The RHU uses about 2 grams of ^{238}Pu to produce 1W of thermal power. Using this as a heat source, Hi-Z produced a thermoelectric device that established a temperature difference of approximately 225°C throughout the device and provided 40 mW of power. The efficiency of the device was approximately 4 percent. Some improvement can be gained through improved insulation and thermoelectrics.

A third approach to creating a micropower device uses radioisotopes to excite phosphors that emit photons, which can then be collected in a standard or modified solar cell. This protects the photovoltaic from damage but increases losses in the system. In addition, the phosphor may be damaged. Typical organic scintillators have energy-conversion efficiencies of 1 percent, whereas inorganic crystals can achieve efficiencies of up to 30 percent. TRACE Photonics, Inc. (Charleston, Illinois), has built a scintillation glass using sol-gel processes with high light-conversion efficiency under radiation exposure (Bower et al., 2002). Current overall efficiencies are approximately 1 percent, but device integration can probably be improved because of the low weight and direct conversion.

Applications of Micropower Sources

All current MEMS devices sold commercially are passive devices. Hence, there is no existing market for micropower sources. Nevertheless, one can envision many future applications of MEMS devices with onboard micropower sources, such as small drug dispensers placed directly into the bloodstream and laboratories-on-a-chip that can carry out real-time blood assays. Researchers at UCLA and UC Berkeley have been investigating so-called "smart-dust" concepts for using wireless communications to create large-scale sensor networks (Kahn et al., 1999). This approach involves distributed sensors that can communicate with each other through a network and thus "provide a new monitoring and control capability for transportation, manufacturing, health care, environmental monitoring, and safety and security" (Asada et al., 1998). These devices will require power for data collection and storage, as well as for the delivery of information between neighboring devices.

A new application of nuclear power is the self-powered cantilever beam produced at the University of Wisconsin (Li et al., 2002). This device, shown in Figure 4, places a conducting cantilever beam in the vicinity of a radioisotope, in this case ^{63}Ni. As the beam collects the electrons emitted from the source, it becomes negatively charged, and the source becomes positively charged. The beam is thus attracted to the

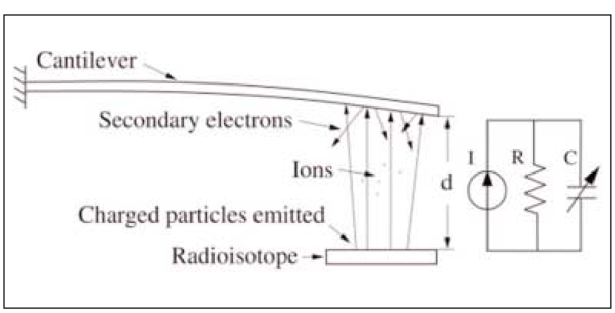


FIGURE 4 Schematic drawing of a self-oscillating cantilever beam. Devices can be modeled as capacitors in parallel with leakage resistors, with most of the leakage resulting from ionization in the gap.

source until contact is made and the device discharges. This causes the beam to be released and return to its original position. The process then repeats itself. Hence, the beam undergoes a repetitive bending and unbending; the period of the oscillation is determined by the strength of the source, the beam stiffness, and the initial separation between the beam and the source. Work is ongoing to produce wireless communication devices based on this design.

Conclusions

Nuclear power is the best, perhaps the only, realistic power source for both long-distance space travel and long-lived, unattended operation of MEMS devices. Much more research will have to be done to optimize the currently available technologies for future applications, but nuclear technologies will clearly provide viable, economic solutions, and they should be given continued attention and support as they approach commercialization.

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A resurgence of the nuclear industry will require overcoming major challenges.

Licensing and Building New Nuclear Infrastructure

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Electricity demand is outpacing supply growth, and experts have calculated that the United States will need new baseload power generation (including nuclear power generation) by 2010 (NEI, 2002a). As part of the Nuclear Power 2010 Initiative, the U.S. Department of Energy (DOE) established the Near-Term Deployment Group (NTDG) to examine prospects for new nuclear plants in the United States in the next decade. According to a recent study by NTDG, a resurgence of the nuclear industry will be influenced by many factors, including economic competitiveness; deregulation of the energy industry; regulatory efficiency; existing infrastructure; the national energy strategy; safety; management of spent fuel; public acceptance; and nonproliferation (DOE, 2001). NTDG also noted that the nuclear industry is experiencing current shortfalls in several important areas (DOE, 2001):

- Qualified and experienced personnel in nuclear energy operations, engineering, radiation protection, and other professional disciplines.
- Qualified suppliers of nuclear equipment and components [including] fabrication capability and capacity for forging large components such as reactor vessels.
- Contractor and architect/engineer organizations with personnel, skills, and experience in nuclear design, engineering, and construction.

Nuclear industry infrastructure can be defined in terms of technologies, facilities, suppliers, and regulatory elements; design and operational engineering and licensing tools; and (perhaps most important) human capital to sustain the industry in the near and long terms. NTDG concluded that, although the industry has adequate industrial and human infrastructure today to build and operate a few new nuclear plants, we cannot be sure that this infrastructure can be expanded quickly enough to achieve the goal of 50 GWe in new nuclear plant installed capacity as laid out in the industry's strategy for the future, *Vision 2020* (NEI, 2002a).

Our industrial and human infrastructure may not expand quickly enough to meet our goals.

The nuclear industry faces infrastructure challenges, untested implementation of new Nuclear Regulatory Commission (NRC) regulations, and uncertainties about the economic competitiveness of new nuclear plants. The near-term deployment of new nuclear-power generation will be a good litmus test of the viability of a larger expansion in nuclear production. According to NTDG, even though the level of additional capacity in the industry goals in *Vision 2020* is meager in terms of overall U.S. energy needs, achieving the goal presents major challenges (DOE, 2001).

Industry and Government Initiatives

Various initiatives have been undertaken by the U.S. nuclear industry and DOE to encourage the domestic development of additional nuclear facilities. In 1998, DOE chartered the Nuclear Energy Research Advisory Committee (NERAC) to advise the agency on nuclear research and development (R&D) issues. NERAC released the *Long-Term Nuclear Technology R&D Plan* in June 2000; NERAC is also responsible for overseeing the development of plans for both NTDG and Generation IV, a project to pursue the development and demonstration of one or more "next-generation" nuclear energy systems that offer advantages in economics, safety, reliability, and sustainability and that could be deployed commercially by 2030 (DOE, 2002). In 1999, DOE initiated the Nuclear Energy Research Initiative (NERI), an R&D program to address long-term issues related to nuclear energy; in 2000, the Nuclear Energy Plant Optimization Program was initiated to focus on the performance of currently operating nuclear plants.

In 2000, NEI formed the industry-wide New Nuclear Power Plant Task Force to identify the market conditions and business structures necessary for the construction of new nuclear power plants in the United States. In April 2001, the task force published the *Integrated Plan for New Nuclear Plants*, which includes a discussion of nuclear infrastructure (NEI, 2001). More recently, NEI announced Vision 2020, an initiative with a goal of adding 50,000 megawatts of new nuclear generating capacity by 2020, along with increases in efficiency power uprates at existing plants equal to an additional 10,000 megawatts of generating capacity (NEI, 2002b).

DOE funding has recently been allocated to advanced reactor development, specifically for the exploration of government/industry cost sharing for the demonstration of early site permitting as part of new NRC licensing processes (which also include provisions for combined licenses and design certifications) and for national laboratory activities associated with fuel testing, code verification and validation, and materials testing associated with new reactor designs (DOE, 2001).

Technological Infrastructure

A number of elements are required to support a new or existing nuclear plant. Suppliers and fabricators of nuclear fuel and safety-related components are clearly essential, as are suppliers of balance-of-plant equipment, construction materials, electronics and instrumentation, and countless other components.

The U.S. fuel-cycle industry has undergone significant changes in the past few years. Future fluctuations in uranium prices, the deployment of new enrichment technologies, significant consolidation of fuel-cycle supply companies, and the possible recycling of spent fuel could all affect the supply chain for nuclear fuel (i.e., mining/milling, conversion and enrichment, and fabrication into ceramic fuel pellets). The NTDG study recognized the sensitivity of new reactor deployment to these factors. NTDG solicited designs for nuclear plants that could be deployed by 2010 and attempted to identify generic issues that could impede their deployment.

Proposals were received from reactor suppliers identifying eight candidate reactor designs. NTDG evaluated these designs to determine the prospects for deployment of a new nuclear plant in the United States by 2010. Candidate reactor technologies were required to demonstrate how they would operate "within credible fuel-cycle industrial structures" assuming a once-through fuel cycle using low-enriched uranium fuel and to "demonstrate the existence of, or a credible plan for, an industrial infrastructure to supply the fuel being proposed." NTDG's design-specific evaluations concluded that the candidates that would use existing fuel-cycle infrastructure could be built by 2010. However, NTDG also concluded that infrastructure expansion to achieve the industry's goal of 50 GWe of new installed capacity by 2020 was a "generic gap" that warrants government and industry action (DOE, 2001).

Siting for new reactors will be greatly influenced by how efficiently 10 CFR Part 52 (the NRC regulation for early site permits, standard design certifications, and combined nuclear plant licenses) can be implemented. NTDG concluded that the federal commitment to cost sharing via government/industry partnerships should include a demonstration of the NRC's early site permit process for a range of likely scenarios. Recently a partnership to evaluate sites for new nuclear plants was announced, and DOE selected three utilities to participate in joint government/industry projects to pursue NRC approval for sites for new nuclear power plants. These projects, the first major elements of DOE's Nuclear Power 2010 Initiative, are intended to "remove one more barrier to seeing the nuclear option fully revived" in the United States. All three companies intend to seek early site permit approvals that would enable them to locate new, advanced-technology nuclear plants at sites owned by the utilities that currently host commercial nuclear power plants (i.e., Dominion Energy's North Anna site in Virginia, Entergy's Grand Gulf site in Mississippi, and Exelon's Clinton site in Illinois). According to a press release on June 24, 2002, DOE expects applications to be submitted by late 2003.

Design concepts for the waste-management component of fuel-cycle infrastructure were also evaluated by NTDG. Each design concept addressed the on-site storage of spent nuclear fuel; but the current lack of a national system for high-level waste disposal is a programmatic gap common to all new technologies. The Nuclear Waste Policy Act (first passed in 1983, amended many times, and still the subject of heated debate) provides for the development of the Yucca Mountain site in Nevada as a mined, geologic repository for high-level waste and the development of a transportation system linking U.S. nuclear power plants, an interim storage facility, and the permanent repository (NEI, 2002c).

The recycling of spent fuel to recover fissile material and long-lived heavy elements would reduce the heat generation and volume of final waste products. When most existing U.S. nuclear plants were built, the industry—encouraged by the federal government—planned to recycle used nuclear fuel by recovering plutonium. In 1979, however, the United States deferred the reprocessing of all commercial used nuclear fuel because of concerns about the possible proliferation of nuclear weapons. Thus, the industry was forced to adopt a once-through, single-use fuel cycle. Reprocessing and recycling are not currently cost effective in the United States, and most of the discussion about recycling is now focused on increasing the capacity of waste repositories and the transmutation of actinides.

The domestic supply of certain reactor components is another long-term concern. Over time, U.S. capacity for fabricating large components with long lead times (e.g., reactor vessels and steam generators) has diminished. NTDG concluded that in most cases, other countries have the necessary capacity and could support the early expansion of nuclear plant construction in the United States, but domestic capabilities will also have to be reestablished (DOE, 2001). General Electric, for example, has indicated that many of the components and much of the hardware (including pumps, heat exchangers, nuclear fuel, control rods, and some internal reactor components, as well as most balance-of-plant equipment) for its advanced boiling water reactor (ABWR) can be produced in the United States. However, the reactor pressure vessel and the large internal components (the same components used for

Over time, U.S. capacity for fabricating large components with long lead times has diminished.

Japanese and Taiwanese ABWRs) will have to be fabricated by foreign suppliers that have maintained their capacity and expertise for fabricating and machining these large components. Foreign suppliers can and do meet U.S. codes and regulations; most foreign countries follow identical or similar codes, such as ASME Section III, IX, and XI, as well as U.S. NRC-imposed regulations and guidelines. NTDG concluded that this area of infrastructure will have to be reconstituted in the United States for economic reasons and that, for some components (particularly reactor vessels), the existing worldwide capacity may not be adequate to support a large expansion of reactor capacity.

Regulatory Infrastructure

NRC is perhaps best known for regulating reactor construction and operation. The agency also regulates nuclear fuel-cycle operations, including the mining, milling, conversion, enrichment, and fabrication of fuel and waste-management facilities. A number of proposed licensing actions and regulatory initiatives are currently under way at the NRC. The most important in terms of near-term continuity in the nuclear industry and adequate energy supply is the renewal of reactor licenses. NRC regulations limit commercial reactor licenses to an initial 40 years (based on economic and antitrust considerations) but also allow licenses to be renewed (NRC, 2002). The license renewal process involves confirmation that structures, systems, and components can continue to perform safely beyond the original term of the operating license.

A key aspect of regulatory development is the efficient implementation of 10CFR Part 52.

License renewal is important for maintaining a significant portion of existing energy production. Currently licensed nuclear reactors generate approximately 20 percent of the electric power produced in the United States. The first plant will reach the end of its original license period in 2006; approximately 10 percent will reach 40 years by the end of 2010; and more than 40 percent will reach 40 years by 2015. As of June 2002, 10 license renewal applications had been granted, and 14 applications were under NRC review; 23 more applications are expected by 2005. License renewal also provides an important collateral benefit by keeping the industry and workforce energized and engaged, thus helping to preserve the institutional and human capital that will be necessary for the near-term deployment of new reactors.

Other high-profile licensing actions related to nuclear industry infrastructure include: an application for a license for a spent-fuel storage facility currently before the NRC and in hearings submitted by Private Fuel Storage (a group of eight electric utility companies in partnership with the Skull Valley Band of Goshute Indians); two pending applications (one from the United States Enrichment Corporation and one from Urenco) for deploying new gas-centrifuge enrichment technologies in the United States; and an application for the construction and subsequent operation of a facility to convert surplus weapons material into commercial fuel as part of an agreement between the United States and Russia to dispose of more than 60 metric tons of surplus plutonium.

A key aspect of regulatory development for near-term deployment is the efficient implementation of 10 CFR Part 52. Created in 1989, this regulation established three new licensing processes for future plants: early site permitting (i.e., NRC approval of a site before a decision has been made to build a plant); design certification (i.e., NRC approval of a standard design); and combined licenses (i.e., a combined construction permit and operating license). These processes could provide a dramatic improvement over the two-step process used for existing U.S. plants. NRC has stated that an application for a combined license that references an early site permit and a certified reactor design could result in an operating license being granted in as little as *one year* (Jeffrey S. Merrifield, NRC commissioner, remarks to American Nuclear Society Conference, June 7, 1994). In actuality, however, only the design certification process has been demonstrated thus far, and it has taken as long as 10 years.

Not surprisingly, NTDG has called the efficient implementation of 10 CFR Part 52 a high priority for short-term deployment and a matter that requires the attention of industry and government. NTDG recommends that four actions be taken: the expediting of the design certification process; the demonstration of the early site permit and combined license processes; the development of generic guidelines to ensure the efficient, safety-focused implementation of key Part 52 processes; and a demonstration of progress toward a new risk-informed, performance-based regulatory framework (DOE, 2001).

DOE's recently announced plans to work in partnership with industry to evaluate sites for new nuclear plants will test the early site permitting component of this regulation. DOE proposes that near-term investments be made as part of the Nuclear Power 2010 Initiative, in part to "demonstrat[e] this key NRC licensing process" (DOE press release, June 24, 2002).

Another evolving area of regulatory infrastructure is NRC's effort to "risk-inform" their regulatory processes. The intent is to improve the regulatory process by incorporating risk insights into regulatory decisions, thereby conserving agency resources and reducing unnecessary burdens on licensees. The risk-informed approach combines risk insights and traditional considerations to focus regulatory and licensee attention on the design and operational issues that are most important to health and safety (NRC, 2001).

In the context of the efficient implementation of 10 CFR Part 52, NTDG calls for a new regulatory framework that is fully risk-informed and performance-based and "go[es] beyond the ongoing efforts to risk-inform 10 CFR Part 50 for current plants" to improve the protection of public health and safety, eliminate regulatory burdens that do not contribute to safety, and "increase the confidence of prospective applicants in the regulatory environment for new plants and encourage business decisions to proceed with new nuclear projects" (DOE, 2001).

Engineering and Licensing Tools

The skills necessary for the development of new infrastructure are largely the same as those necessary for the maintenance of existing facilities. In fact, efforts to continue improving existing facilities not only provide a performance benefit to facility stakeholders, they also help ensure that human and technological resources will be available for the development of new facilities. Thus, ongoing improvements to existing facilities are extremely important. From 1990 to 2000, for instance, improved efficiency at U.S. nuclear power plants provided the production equivalent of constructing 22 new 1,000-MW power plants—enough power to provide 22 percent of new electricity demand during that decade (NEI, 2002d). So, not only are there ample economic reasons for continuing to pursue improvements, there are also substantial collateral benefits, such as ensuring the ongoing development of technological tools and the engagement of human capital in nuclear technologies.

A risk-informed approach to regulatory decisions and processes will focus attention on health and safety.

Computer Technology

The most dramatic contributor to changes in design tools in the last 25 years has been computer technology. With today's computational speeds, optimization and simplification of new plant design and construction seems to be limited only by the imagination. One has only to compare modern development tools to historical methods to appreciate the change.

Core physics simulations provide a good example. In the 1970s, a typical simulation used a lattice-cell code that modeled a single fuel pin (or rod) surrounded by an infinite array of homogenized media created to look like the adjacent pins. Approximations were used to model assembly-averaged thermal-hydraulic effects and axial representations, and in-core fuel management was performed by trial-and-error shuffle schemes, using manual iterations until cycle length and power peaking requirements were met.

Modern design software typically uses a two-dimensional code that models a full fuel assembly and uses advanced ray tracing, collision probability, or Monte Carlo techniques. The core simulator is a three-dimensional advanced nodal code with pin reconstruction techniques and explicit thermal-hydraulic modeling and is capable of three-dimensional space-time calculations. Core-loading pattern development has been automated, using advanced nodal codes coupled with simulated annealing techniques to develop core-loading patterns that meet predetermined limits on pin peaking, cycle length, and other attributes to minimize fuel cost within applicable core physics limits.

Another dramatic example of the benefits of increased computer power is the advent of computer-aided design (CAD) and engineering, which not only have enabled the development of increasingly complex and sophisticated civil/structural models, but have also significantly eased the burden of physical-interference modeling and facility-configuration control. Designs in the 1970s were modeled primarily on paper and required hundreds of individual drawings. Plastic and wooden scale models were often painstakingly fabricated and maintained (Figure 1) to help identify costly interferences between electrical, mechanical, and structural components that could be missed in two-dimensional drawings and to assist with the visualization of designs and changes to those designs.

In the last decade or so, the development of more and more sophisticated models (Figure 2) as the basis of design has improved the coordination of drawings, accelerated the communication of design alternatives, and significantly reduced the requirements for field reworking (Bernstein, 2001). Using a central data representation results in improved integration and coordination among various design documents and between design disciplines. In addition, procurement, construction, and subsequent ongoing configuration-management of the facility—a key aspect of the design, licensing, operation, and maintenance of a nuclear facility—have been greatly facilitated (Bernstein, 2001).

Human Infrastructure

One of the most important aspects of nuclear infrastructure, particularly for a domestic resurgence of the industry, is the development of human resources. The nuclear industry faces the dual challenge of an aging workforce and a growing gap between its employment needs and the number of graduating students. Replacement of the aging workforce is essential for both existing plants and new facilities.

NTDG cited key initiatives dealing with human resources at DOE, NEI, and the American Nuclear Society and recommended that these initiatives be maintained and strengthened (DOE, 2001). On June 10, 2002, DOE announced the establishment of a new program, Innovations in Nuclear Infrastructure and Education, that offers several million dollars in awards to university consortia to encourage investments in programs on research reactors and nuclear engineering and in strategic partnerships with national laboratories and industry. At the same time, DOE announced that it would award more than 100 scholarships, fellowships, and grants to nuclear science/engineering institutions and students.

Other public and private efforts to bolster the educational infrastructure for the nuclear industry are under way throughout the United States. As a result, almost every university and national laboratory associated with nuclear science and engineering now offers scholarships and fellowship programs.

Conclusion

The potential for a resurgence of the nuclear industry in the United States is a function of many factors. New technologies continue to be developed, but key

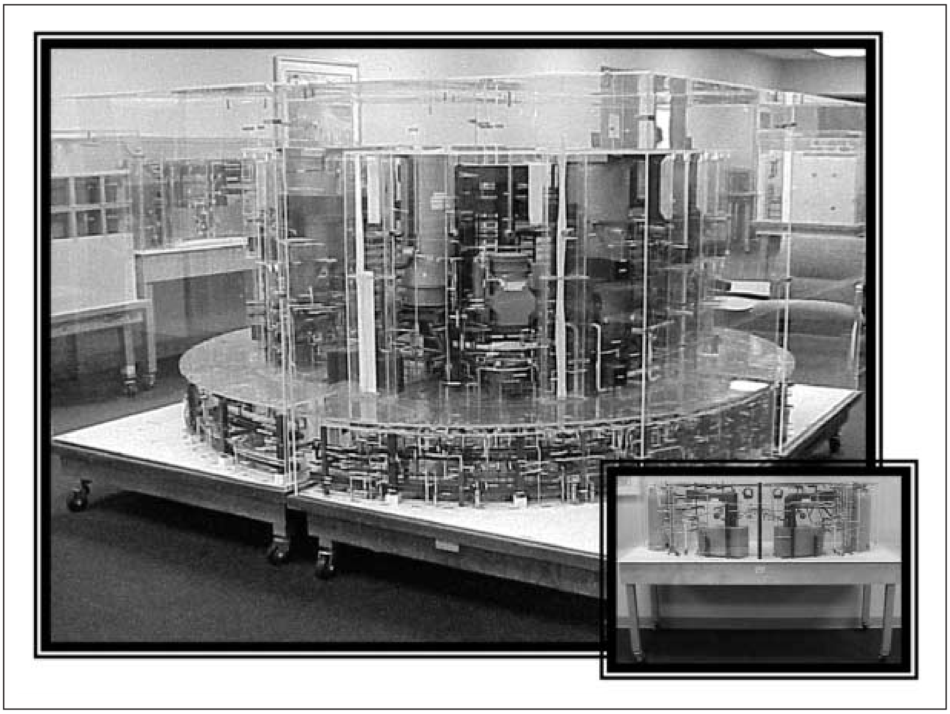

FIGURE 1 Scale model for the McGuire Nuclear Station Reactor fabricated to help identify interferences. Source: Photo courtesy of Duke Energy.

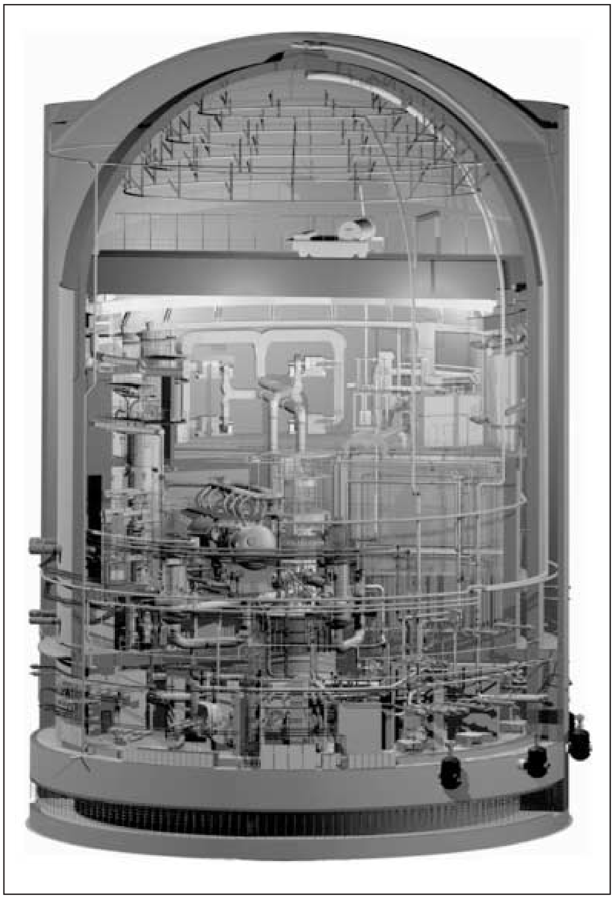

FIGURE 2 Model of 1,000 MW reactor (Lianyungang Unit 1), Elias Mayer, Fortum Engineering, Ltd., Vantaa, Finland. Source: Graphic courtesy of Process, Power and Offshore Division, Intergraph Corporation.

areas of infrastructure to support expansion must be maintained and (in many cases) expanded for a future nuclear option to be sustainable. Although significant challenges lie ahead, a number of government, industry, and joint public/private efforts are under way to facilitate this expansion. The reestablishment of the industrial infrastructure that supplies materials and components, the continued improvement and demonstration of effective regulatory processes, and the development of essential human resources are all critical factors to the future of the nuclear industry in the United States.

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NAE News and Notes

2002 NAE Annual Meeting

NAE members, foreign associates, and guests gathered in Washington, D.C., this October for the 2002 Annual Meeting. The meeting began on October 5 with an orientation followed by the NAE Council dinner honoring the 74 new members and seven foreign associates.

The public session on October 6 was opened by NAE chair, **George M.C. Fisher**. President **Wm. A. Wulf** then addressed the group. He reviewed the purpose of the strategic plan, "to promote the technological health of the nation," and the necessity of engineers providing the leadership to fulfill this goal. To accomplish this and to maintain our reputation and effectiveness, Wulf said, NAE will have to rethink its traditional role as passive responder to questions posed by the federal government. Engineers, individually and collectively, must be willing to confront issues that are technologically grounded but require political action. (The complete text of Wulf's remarks begins on page 42.) The induction of the Class of 2002 followed President Wulf's address.

The program continued with the presentation of the 2002 Founders Award to **Stuart W. Churchill**, Carl V.S. Patterson Professor Emeritus of Chemical Engineering at the University of Pennsylvania. Churchill was recognized "for outstanding leadership in research, education, and professional service, and for continuing contributions in combustion, heat transfer, and fluid dynamics for over half a century." (The complete text of Churchill's remarks begins on page 50.)

For the second year talks were given by recipients of the Lillian M. Gilbreth Lectureships, which recognize outstanding young engineers and bring them to the attention of NAE members. The first speaker, Andrea Goldsmith, associate professor of electrical engineering at Stanford University, discussed design challenges for future wireless systems. Challenges include capacity limits of the wireless channel and limits at the hardware, link, network, and application levels. The second speaker, Cynthia Riley, biofuels technology manager at the National Renewable Energy Laboratory, addressed the issue of biomass energy, particularly the production of alternative transportation fuels from biomass.

President Wulf then introduced Eli Fromm, recipient of the inaugural 2002 Bernard M. Gordon Prize for Innovation in Engineering and Technology Education. Fromm was recognized "for innovation that combines technical, societal, and experiential learning into an integrated undergraduate engineering

Class of 2002

Lillian M. Gilbreth lecturers, Cynthia Riley (left) and Andrea Goldsmith

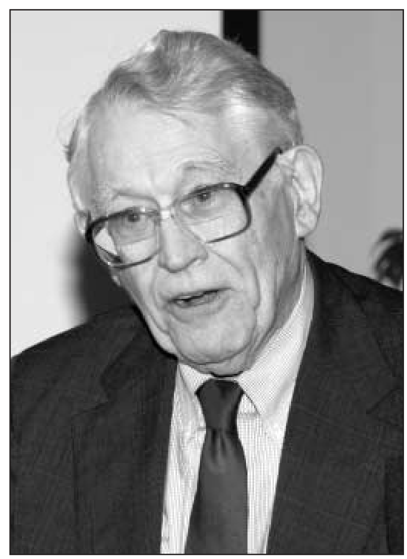
curriculum." Dr. Fromm is the Roy A. Brothers University Professor, professor of electrical and computer engineering, and director of the Center for Educational Research in the College of Engineering, Drexel University.

A reception following the program included a book signing by **H. Guyford Stever**, former NAE foreign secretary, whose memoir was recently published by the Joseph Henry Press. A symposium honoring Dr. Stever was held the next morning, following the Annual Business Session. The symposium was moderated by Philip M. Smith, former executive officer of the National Research Council, who worked with Dr. Stever at both the National Science Foundation and the White House Office of Science and Technology Policy. Speakers included Marye Anne Fox, North Carolina State University; **William J. Perry**, Stanford University; Ralph Cicerone, University of California, Irvine; **John P. Holdren**, Harvard University; **Arden L. Bement, Jr.**, National Institute of Standards and Technology; and Norman P. Neureiter, science and technology advisor to the secretary of state. On Monday afternoon, members and foreign associates attended section meetings at the new National Academies building at 500 Fifth Street, N.W., in Washington.

The annual reception and dinner dance were held at the J.W. Marriott Hotel. Musician, comedian, and PBS personality Mark Russell provided the entertainment, and the Doc Scantlin orchestra provided the music.

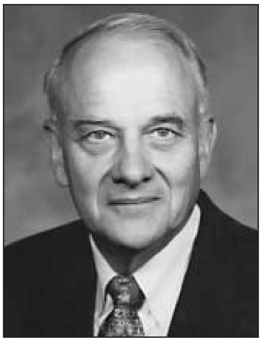
The final event of the meeting, a technical symposium, Computing Meets the Physical World, was held on Tuesday, October 8. **David D. Clark** presided; speakers included **Butler Lampson**, Microsoft; Manuela Veloso, Carnegie Mellon University; David Culler and Kristofer Pister, both of the University of California, Berkeley; Chris Diorio and Thomas Daniel, University of Washington; and Eric Grimson, Massachusetts Institute of Technology.

The next annual meeting is scheduled for October 12–14, 2003. Mark your calendars now!



H. Guyford Stever

President's Remarks



Wm. A. Wulf

These remarks were delivered at the Annual Meeting on October 6, 2002.

It is an immense honor to welcome our new members and foreign associates. You must feel honored as well; my own induction is one of my fondest memories. The academy is renewed and enriched by each new class. Your knowledge and experience enable us to continue to play a unique and invaluable role in service to our country. I also want to acknowledge the families and friends of the members of the new class. I know that none of those being inducted would be here if it weren't for their support.

I am going to raise a somewhat weighty issue with you today, so I hope you'll forgive me for diving right in. By way of context, I should explain that in 1999, after two years of preparation, NAE proposed a new strategic plan. Every year at its August meeting the NAE Council reviews the plan and sets operational objectives for the coming year. This year the council affirmed the new plan. But rather than talk about the plan itself, I want to talk about a question that arose in our discussion of it.

As many of you know, the National Academies operate under an 1863 charter from the U.S. Congress that calls on us to provide advice to the government on issues of science and technology, and to do so without compensation whenever we are asked. Our role is unique among academies around the world, and in that role, we have been of immense value to the United States. But it's a passive role. That is, *if and when* we are asked, we provide advice to the government. By contrast, the new strategic plan starts with the words: "to promote the technological health of the nation . . . " That may sound innocent enough—but notice that the words do *not* say wait to be asked or only provide advice or limit our target audience to the federal government. The new strategy is a much broader and much more proactive mandate.

In the course of our discussions, a question arose about the need for technical leadership in terms of the new policy. As president of NAE, I am at the nexus of science, engineering, and public policy. Every day I see that technologically astute leadership is essential to wise governance in our increasingly technology-dominated world. Questions of technology are integral to many of the most important issues facing the country—energy, the environment, defense, both at home and abroad, and on and on. These issues require more than a superficial knowledge of engineering and technology. They require the sort of deep, visceral understanding that only comes with the practice of engineering.

In the context of an extended discussion of the profound need for technically savvy leadership, the following question was raised: Although there is no doubt that we need technologically astute leadership, will engineers "stand up" to fill that need? Are engineers, both individually and collectively, willing to provide that kind of leadership? When the question was first asked, I thought it was a "no brainer." Of course we would! On reflection, however, I am not so sure—for several reasons:

1. The culture of engineering is for engineers to be unassuming, to be inconspicuous.
2. The culture of engineering rewards technical achievement, not leadership. How often have you heard someone say, "She isn't an engineer any longer; she's become a manager."
3. The culture of engineering proscribes our giving advice, except on technical matters. How often have you heard someone say, "That's a political question; we have nothing to contribute."
4. The culture and practice of the NAE reflect the culture of engineering. We regularly decline to undertake studies if the answer isn't technical.

Perhaps one of the most telling reflections of our reluctance to stand up is that only eight members of Congress have engineering degrees (two of whom also have law degrees). That's eight out of 535! That's 1.5 percent, *much* lower than our representation in the population that might be qualified for office. Engineers just don't seek elective office in this country. That's quite a contrast with countries like China where the prime minister and about a third of the ministers are engineers. There's nothing in the genetic makeup of people who choose to be engineers that makes them shy away from public office; it's something in the culture of this country. Don't misunderstand me. I believe we *should* stand up. But we're going to have to ask ourselves some tough questions about what we value and how we preserve those values when we stand up—or, indeed, perhaps decide that we won't. Either way, it should be a conscious decision.

My summer reading this year included *Tuxedo Park*, the story of the people who provided technical leadership just before and during World War II. One of them, Vannevar Bush, was an engineer, but most of them were physicists. I found it interesting that they faced some of the same cultural issues we face now. They resolved them fairly quickly, under the pressure of the war—but there is no doubt that radar, the Norton bombsight, the proximity fuse, and the atomic bomb, which were crucial to winning the war and saved millions of lives, were possible only because the physics community stood up.

I know of no organization other than the NAE that can begin the conversation about standing up. I am going to use the events of 9/11 as a concrete framework for my remarks, but I believe the general issues apply to a much broader range of topics. This discussion can be divided into two broad sets of issues. The first set, which relates to the use of technology in countering terrorism, will be fairly comfortable territory. The second set may be less comfortable because, although it is technologically grounded (that is, one needs a technical background for an in-depth understanding of the issues), the required response isn't necessarily technical. When talking about these kinds of issues, we must ask ourselves whether we're prepared to stand up.

Let's begin with the familiar ground. When Bill Perry was secretary of defense, he liked to point out that one of the reasons we won the Cold War was that we never actually had to fight a conventional, non-nuclear war because NATO would be a credible adversary in a conventional war. We were credible in spite of the significant numerical advantage—in both troops and armament—of the Soviet Union and the Warsaw Pact. NATO was a credible adversary as the result of the "offset strategy." We offset their numerical advantage with superior technology. Our troops could locate, identify, target, and destroy potential attackers with far greater accuracy, speed, and lethality than Warsaw Pact troops. MAD (mutually assured destruction) may have prevented a nuclear war, but the offset strategy was a major component of the larger strategy for preventing a conventional war.

We are now faced with a very different adversary with a different advantage, and we need different technologies to offset those advantages. But the principal is the same. With technology, specific threats can be detected and countered; for example, sensors can detect explosives and chemical and biological agents. Technology can also reduce the costs of security. Some of the technologies of most interest can reduce the costs to our lifestyle *and* our civil liberties, rather like a metal detector, which is both faster and less intrusive than a pat-down search.

As a trusted advisor to the federal government, the National Academies will undoubtedly play an important role in identifying and validating technologies; in fact, we are already up to our eyebrows in doing exactly that. More than 50 studies and activities are going on. Some are long term, such as a study requested by the President's science advisor, Jack Marburger, for an R&D agenda. That report, *Making the Nation Safer*, was published in June. Other activities are shorter term, such as advising the FBI on its next-generation computer system.

These activities are very, very important, and the Academies are uniquely capable of doing them. In fact, we've been doing them since shortly after the founding of the National Academy of Sciences (NAS) in 1863. This is a familiar, comfortable role, and we have no trouble standing up in this way. But now let me shift to the second class of issues—technologically based issues that require advice that is not necessarily technical—and may not even be intended for the government. I am going to use four examples: (1) the balance between openness and national security; (2) student visas; (3) the root causes of terrorism; and (4) need-driven basic research.

In each case, engineers understand the issues far better than either the general public or most policy makers. We understand the issues because of our experience and our technical expertise. But the answers aren't technical, and may in fact be political. With these examples, I invite you to think about whether, and if so how, engineers should stand up.

Openness vs National Security

During the Cold War, the government and the technical community developed a consensus on the balance between openness and security, especially with respect to nuclear weapons technology. In fact, we came to understand that a certain degree of openness *enhanced* our security. For example, MAD, the policy of mutually assured destruction, *depended* on each side knowing enough about the other's capability to ensure that neither made a miscalculation.

More generally, openness in research allowed researchers to make rapid progress toward a deeper understanding of nature and allowed engineers to translate that understanding into a better life for everyone. Of course, some things had to be classified to ensure our national security. But the people involved in setting policy understood the wisdom of building high fences around small areas. That is, we opted in favor of openness, except in the areas where secrecy was essential—and those secrets we protected vigorously.

Since 9/11 and the anthrax incidents of last fall, there has been a knee-jerk response to reduce openness. For example, we have restricted access of foreign nationals to national laboratories, barred some foreign nationals from attending certain college courses (such as classes in cybersecurity), and required a government review of research papers before they are published. I believe we must find a new balance point between openness and security; the situation today is quite different (in terms of the adversary and the relevant technologies) from the situation during the Cold War. In many cases, the people advocating these restrictions have little experience with the openness/security balance of the past. Specifically, they are not aware that openness actually contributed to our real security. That lack of experience is leading to overly cautious, and potentially counterproductive, behavior. Unless the engineering community, which by and large has much more experience with national defense than the scientific community, becomes engaged, it is unlikely that we will find the optimal new balance point.

The issue of openness and security arises from a combination of technical concerns and security concerns, both of which we know a lot about. But the actions indicated are definitely not technical. Should we stand up? If so, how?

Student Visas

Student visas may be a special case of the previous example. As many of you in academia know, it is now much more difficult for students to get visas to enter the United States—especially for young men from Asia and the Middle East. You also know that foreign students and immigrants have contributed enormously to the welfare of this country. As a first-generation immigrant, I have a visceral sense of the contributions that my father, and all of the immigrants entering today, have made to the United States. Even students who return to their native countries can be of immense value to the United States. Because they understand us and our values, they are often our best spokespersons.

Two years ago my wife and I, with NAS Presdient Bruce Alberts and his wife, visited our counterpart academy in Iran, a country that President Bush has labeled part of the "axis of evil." That may or may not be true—I'm not an expert, and I haven't been briefed on the information that prompted that remark. However, I quickly learned that Iranian universities and the Iranian academy are filled with people who are influential in their country, have been educated in the West (the United States in particular), are sympathetic to our goals and values, and are anxious to have better relations with us.

No one outside the research community can possibly have the kind of in-depth, gut-level understanding of the technical contributions and the ambassadorial role of our foreign students. At the same time, however, we must take into account that some of the terrorists who hijacked the four planes last September *were* here on student visas. Therefore, benign neglect in granting and tracking students is *no longer* acceptable. Sensible precautions are certainly in order. Just as with openness, we must find a new balance point.

Again I ask the same basic question. We have experience that is highly relevant to resetting the balance point. Should we stand up? If so, how?

Root Causes of Terrorism

The NAE is conducting a study to help channel resources to ameliorate our most serious vulnerabilities. Rather than just fortifying airports, we need to take a broad look at the kinds of vulnerabilities that exist and the risks they pose—that is, the probability of an incident and the consequences of that incident—associated with each vulnerability. The resulting assessment should be the basis for our investments in protection.

As a result of my involvement in

this study, I now know that we have a huge number of vulnerabilities—vulnerabilities that can have cataclysmic consequences. I now know what engineers in this area have known for a long time—that we cannot defend against all threats. We can move the target a bit, but if we have a perfect defense against the N most serious threats, terrorists will simply select the N+1 threat. So we can move the target, but we cannot create a perfect shield.

Much the same is true of mounting an offense against networked terrorist organizations. Al-Qaeda is not likely to conveniently (for us) amass again in an area where we can use our Cold War era armaments to advantage. Oddly, the same technical properties that make the Internet robust to failure make the human network of terrorists robust to failure. I think only engineers can appreciate that statement in depth. The popular press and our political leaders, by contrast, seem to be operating on the assumption that a combination of defensive actions at home and offensive actions abroad can keep us safe. As we know, they won't.

In the long run, we will have to deal with the reasons terrorists hate us—what some have called the root causes of terrorism. I am not an expert, although I have been getting a crash course for the last 13 months. But I've learned that terrorism arises from a complex interplay of geopolitics, religion, regional/ethnic pride, economics, and other factors. The eventual solution will have to address a broad spectrum of issues, including bringing democracy, freedom, justice, and especially hope, to potential terrorists. I do not want to delve into all that now, except to note that poverty and hopelessness breed desperation and create a climate for terrorism.

If we are really going to eliminate terrorists, if we are really going to make ourselves safe, we will have to address the issues that affect the quality of life in developing countries, and engineers will play a central role in this. That's not a fuzzy, humanitarian, do-good statement. It's a national security statement. It's also not a complete statement, because the issues of democracy, freedom, justice, and hope must also be addressed. But a decent quality of life is a necessary precursor.

Engineers have the expertise and experience. Relatively straightforward risk analysis shows that we cannot defend against all threats. Should we stand up and explore the consequences for national policy? If so, how?

Need-Driven Basic Research

My fourth and last example is directed at us rather than at the government. At the end of World War II, Vannevar Bush submitted a report to the president, *Science, the Endless Frontier*, which set the tone for federal support of research for the next 50 years. In his report, Vannevar Bush defined the difference between basic and applied research. He argued that mission agencies, such as the Department of Defense (DOD) and the Department of Energy (DOE) could not be expected to support basic research. The demands of their mission, he said, would drive out basic research in favor of applied research. Ultimately, that argument led to the creation of a new agency—the National Science Foundation—to support basic research. In the intervening 50 years, the academic community has reinforced this argument many times. But is it true? And is it appropriate?

Unfortunately, it's not true. First, mission agencies like DOD, DOE, NASA, and others *do* support basic research. In fact, they are the principal funders of certain areas of basic research! Second, as pointed out by Donald Stokes in his book, *Pasteur's Quadrant*, the basic/applied dichotomy is too simplistic. Not all basic research is motivated by intellectual curiosity alone. Sometimes it is motivated by both curiosity and practical concerns. As a prime example, Stokes cites Pasteur's germ theory of disease, which Pasteur discovered while he was in pursuit of very practical concerns related to the brewing of beer.

I believe some basic research questions are also motivated by practical concerns about counterterrorism. I know this is true in my field of computer security, and I believe it is true in virtually all fields. The question remains. Are we, especially we academic engineers, prepared to stand up and let our intellectual pursuits be at least partly directed by the nation's needs? Are we willing, for example, to devote a fraction of our capacity to addressing the needs of the developing world in order to reduce the risks here at home? The physicists at Tuxedo Park, in the Rad Laboratory, the Manhattan Project, and thousands of others did that during World War II. Are we prepared to do it now?

Conclusion

I chose these four examples because each of them highlights a different aspect of the basic question of whether engineers, *individually* and *collectively as an Academy*, are prepared to step beyond our traditional role, although in that role we have been invaluable to the nation. This is hardly an idle question. Much of the authority of the Academies rests on our reputation for providing authoritative, fact-based reports. There is some danger that we could tarnish that reputation. If the Academy stands up now, we must carefully consider how to do it in a way that enhances rather than detracts from our reputation—and hence our effectiveness.

In conclusion, let me note that the increasing relevance and influence of the Academies is stressful in many ways, but it reflects the importance of engineering and science in the modern world. Our relevance demands that we rethink our traditional role as passive responders to questions posed by the government. Our relevance may also be pushing us toward the role of commentators on issues with technological roots that require nontechnical action. Think about it. Are we prepared to stand up and take on that role? If so, how? Your officers and council members will be grappling with these questions, and we welcome your input! The urgency of these questions underscores why you, our new members, are so important to the Academy and to the country. Your knowledge and expertise make it possible for us to provide our policy makers with the best engineering and scientific advice available anywhere.

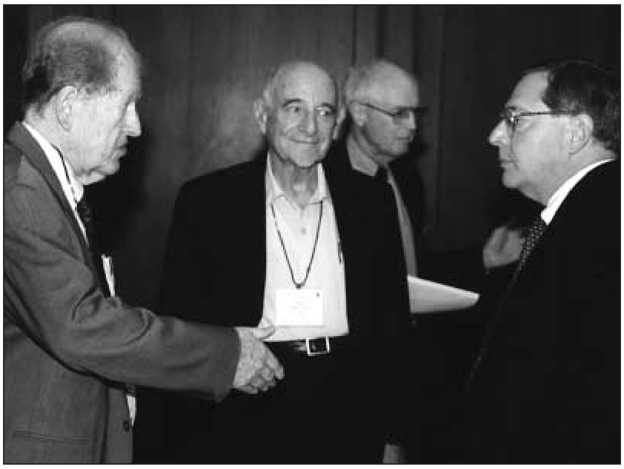
Development Activities at the 2002 Annual Meeting

Anita Jones and Bill Wulf share a laugh with Muriel Feely and George Clemow.

Bill Wulf chats with Mildred Willenbrock and Frances Elliott.

The Reunion Program was created in 2000 to enable spouses of deceased NAE members to remain engaged in Academy activities. Members of the group—now numbering 50—receive NAE publications, are invited to attend regional reunions and a reunion brunch during the NAE Annual Meeting, and other special activities. This year the brunch was hosted by NAE member **Anita Jones**, spouse of NAE President **Bill Wulf**. For more information on the Reunion Program, contact Tess Samuel at (202) 334-2431 or *tsamuel@nas.edu*.

More than 50 Academy members participated in the Annual Meeting seminar, "Estate Planning from Your Spouse's Perspective."



Then members took the opportunity to address specific questions to nationally respected estate planning attorney Frank Mirabello (right).

The Academy offers a range of resources to assist members with estate planning. Resources include a quarterly newsletter (*Insight on Estate Planning*), an online information center at *NationalAcademies.org/Insight*, and free access to estate planning attorneys retained by the Academy. At the recent NAE Annual Meeting, members participated in an estate planning seminar, Estate Planning from Your Spouse's Perspective. For more information on estate planning and estate-based philanthropy, contact Merrill Meadow at (202) 334-2431 or *mmeadow@nas.edu*.

U.S. Frontiers of Engineering and Japan-America Frontiers of Engineering

Mary Czerwinski from Microsoft gave a presentation on human factors engineering implications for novel software user-interface design.

The NAE held two Frontiers of Engineering (FOE) symposia, one in September and one in October. The eighth U.S. Frontiers of Engineering meeting was held at the Beckman Center in Irvine, California, September 19–21, and the second Japan-America Frontiers of Engineering (JAFOE) meeting was held October 24–26 in Tokyo, Japan.

Approximately 100 engineers attended the U.S. FOE Symposium, where talks covered topics in the areas of chemical and molecular engineering, human factors engineering, the future of nuclear energy, and quantum computing. The session on chemical and molecular engineering covered cutting-edge research in the field. Talks were focused on fuel cells, the computational design of materials, and state-of-the-art computational fluid dynamics and its applications in twenty-first century industry. For the first time, a session on human-factors engineering was included in the program. Four speakers provided an overview of the field with examples of human-factors interventions in complex sociotechnical systems, applications in surface transportation systems, human-computer interactions in the context of large panel displays, and direct brain-interface technology. The session on the future of nuclear energy covered a wide range of issues related to the potential of nuclear energy. Talks focused on advanced nuclear reactor technologies, nuclear infrastructure, sustainable nuclear fission energy, space nuclear power, and nuclear energy for microelectromechanical systems. The symposium concluded with a session on quantum computing. Speakers addressed the status of research on large-scale quantum computers, quantum cryptography, ion-trap quantum computation, and scalable quantum computing using solid-state devices. Extended summaries of symposium presentations will be published by the National Academies Press in February 2003.

For the first time, six engineering graduate students from institutions across the country participated in the meeting. Their attendance was made possible by a grant from IBM Corporation.

This year's dinner speaker was **Andrew J. Viterbi**, president of Viterbi Group and cofounder of Qualcomm, Inc., who spoke on the development of digital communication and the wireless industry. **Michael L. Corradini**, chair, Engineering Physics Department and professor of nuclear engineering and engineering physics at the University of Wisconsin-Madison chaired the organizing committee and the symposium. The 2003 organizing committee, chaired by **Pablo G. Debenedetti**, Class of 1950 Professor and Chair, Department of Chemical Engineering, Princeton University, has begun planning for the next U.S. Frontiers meeting, which will be held September 18–20, 2003, at the Beckman Center.

Funding for the September 2002 U.S. Frontiers of Engineering

Participants had numerous opportunities for informal discussion.

Symposium was provided by the Defense Advanced Research Projects Agency, the U.S. Department of Defense (DDR&E-Research), the Air Force Office of Scientific Research, the National Aeronautics and Space Administration, Microsoft Corporation, Ford Motor Company, IBM Corporation, and Cummins, Inc.

The second Japan-America Frontiers of Engineering (JAFOE) Symposium was attended by approximately 60 engineers—30 from each country. Four topics were covered at the meeting: bioengineering, synthesis and applications of nanomaterials, sustainable manufacturing, and pervasive computing. Presentations were given by two Japanese and two Americans in each area. The topics included molecular engineering of gene and stem-cell therapeutics, advanced nanocarbon materials, design for the environment and recycling, and computer-augmented environments. The talks elicited a great deal of discussion and many brisk Q&A sessions. Other highlights included poster sessions where each participant talked about his/her technical work or research; a tour of the meeting site, the National Museum of Emerging Science and Innovation; a visit to the Superconductivity Research Laboratory followed by dinner and a speech by Dr. Shoji Tanaka, director-general of the laboratory; and visits to the Edo-Tokyo Museum and the Asakusa district of Tokyo.

NAE member **Robert H. Wagoner**, George R. Smith Chair of Engineering, Department of Materials Science and Engineering, Ohio State University, and Hideaki Matsubara, deputy laboratory director, Japan Fine Ceramics Center, cochaired the organizing committee and the symposium. The JAFOE symposium was organized in cooperation with the Engineering Academy of Japan and the Japan Science and Technology Corporation (JST). Funding was provided by JST, the National Science Foundation, the Office of Naval Research, and the Army Research Office. Plans are under way for a third JAFOE meeting in the United States on November 20–22, 2003, at the Beckman Center.

Participants had an opportunity to learn about each other's work during the poster sessions.

An organizing committee for the 2003 meeting, chaired by **James G. Fujimoto**, professor, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, and Kazuhiro Sakurada, division head, Tokyo Research Laboratories, Kyowa Hakko Kogyo Co., met in Tokyo. The program will include bioengineering, information and network technology, large-scale civil systems, and energy.

NAE has hosted the U.S. Frontiers of Engineering meeting since 1995 and JAFOE meetings since 2000. (NAE also has a bilateral Frontiers program with Germany, which began in 1998.) The meetings bring together outstanding young engineers (30 to 45 years old) from industry, academia, and government at a relatively early point in their careers. Frontiers provides an opportunity for young engineers to learn about the cutting-edge developments, techniques, and approaches in many fields. The meeting also facilitates the establishment of contacts and collaboration among the next generation of engineering leaders.

For more information about the symposium series or to nominate an outstanding engineer to participate in future meetings, contact Janet Hunziker at the NAE Program Office at (202) 334-1571 or by e-mail at *jhunziker@nae.edu*.

2002 Founders Award Presented to Stuart W. Churchill

George M.C. Fisher, Stuart W. Churchill, Wm. A. Wulf, and Wesley L. Harris.

The 2002 Founders Award was presented to Stuart W. Churchill, Carl V.S. Patterson Professor Emeritus of Chemical and Biomolecular Engineering, University of Pennsylvania, "for outstanding leadership in research, education, and professional service, and for continuing contributions in combustion, heat transfer, and fluid dynamics for over half a century." These remarks were delivered during the NAE Annual Meeting on October 6, 2002.

When **Bill Wulf** called with the news concerning this award, I was awestruck. I was even more awestruck when I reviewed the list of previous recipients. I wish to express my sincere gratitude to my nominators and to the Awards Committee for choosing me for this great and unexpected honor. Many people have contributed to my career, and thereby to this award, too many to acknowledge individually, so I will only mention a few in the context of my remarks. I will focus today on the characteristics and benefits of an education in engineering, both formal and informal. I hope you will indulge me in choosing a topic that is as familiar to you as it is to me and indulge me further in choosing examples from my own career.

Even early in our undergraduate studies, we all began to appreciate the insight and power associated with the engineering method of analyzing physical and chemical behavior objectively in mathematical and conceptual terms. This capability distinguishes engineers from everyone but scientists, and our willingness, even eagerness, to apply our analyses to practical ends, no matter how complex, distinguishes us somewhat even from them. A second characteristic of engineering, less well known to the general public, is the tradition of exposing work-in-progress to untrammeled criticism by our peers.

An engineering education influences our daily lives as well as our professional work. As an extreme example, my youngest brother studied engineering during his military service in World War II but decided to go to law school after the war. Now a federal district judge, he says his engineering education helps him in decision making, and the term BSE in his biography intimidates attorneys and discourages them from trying to flimflam him. My other brother, after a few years of practice as an engineer, became a businessman in partnership with my father. He too says his engineering education has been invaluable in his second career.

Growing up in a small agricultural community in Michigan in the depths of the Great Depression, I knew almost nothing about engineering. An outside counselor brought in by my high school suggested that I consider chemical engineering as a field of study in college because of my penchant for mathematics and chemistry. My father then suggested that I discuss the possibility with the only engineer in our community, expecting (and hoping) that he would discourage me. That young man, embittered by his inability to find a job as an electrical engineer three years after graduation, did his best to discourage me. But, with the irrepressibility of youth, I bravely chose to enter the unknown world of engineering.

At the University of Michigan, I was soon inspired to emulate my teachers, particularly Alfred H. White and George Granger Brown, who related our daily assignments to their work as researchers and consultants, and **Donald L. Katz**, with whom I did undergraduate research that resulted in my first publication. One of my teachers in mathematics, Clyde E. Love, encouraged me to keep that option open, and I crowded the requirements for a degree in mathematics into my schedule, along with the marching and concert bands. The marginal effort I made for that second degree in mathematics has had a subtle but lasting effect on my career in terms of capability and recognition.

The outbreak of World War II prevented me from following my inclination to go to graduate school and become a teacher, but in the long run that unwelcome circumstance proved to be fortuitous. Instead of continuing my formal education, I worked for four years for the Shell Oil Company, where, because of the critical times, I was given extraordinary responsibilities. My tasks were especially satisfying because they clearly contributed to the national war effort. The informal education I received in that vibrant environment was perhaps equal in importance to my formal undergraduate education.

Several engineers with Ph.D.s who worked in refinery operations at Shell Oil rather than research became my new role models because they knew so much more than I did about what went on in those huge "black boxes." Their example furthered my desire to do graduate work, whether or not I became a teacher.

When the war ended, however, I was diverted once again from that ambition—this time by the challenge of becoming the only engineer outside of management in a small start-up chemical plant based on an untested new process. That venture was almost too successful. The original owners of the Frontier Chemical Company cashed out their capital gains after only one year and thereby broke their promise to include me in the ownership of the company. The loss of any hope of a stake in that enterprise precipitated my long-deferred return to graduate school. After more than half a century, my experiences at Shell Oil and Frontier Chemical continue to be major resources in my teaching. Processes and technology change rapidly with time, but the principles of engineering design and operation change more slowly. Most current teachers have not had the benefit of industrial experience, and this distinction was one reason for my willingness to continue teaching a terminal design course 13 years after my nominal retirement.

When I returned to graduate school, my industrial experience and greater maturity somewhat counterbalanced my academic rustiness and helped me cope with the significant changes in the curriculum that had occurred during the intervening five years. In graduate school, I was once again greatly inspired by my teachers and eventual colleagues at the University of Michigan, especially by Robert Roy White, Joseph J. Martin, and **Myron Tribus**, as well as those I already mentioned. My graduate career was somewhat unusual because I took many advanced courses in physics and chemistry, as well as in mathematics, an opportunity and privilege now denied to doctoral candidates because of wholly contract-based funding. My extensive, high-level course work in fields other than chemical engineering proved to be an invaluable resource in my subsequent academic career. It gave me the confidence to expand the horizons of my teaching and research and the courage to interact with colleagues in other fields, such as Peter Debye (physical chemistry), Subrahmanyan Chandrasekhar (astrophysics), Ruel V. Churchill (mathematics), and George Uhlenbeck (physics). The latter once told me that a physicist would know better than to work on the problem we were discussing but that I would probably succeed because engineers are willing to settle for approximate, numerical answers. My collaborators when I first became a faculty member, especially Alexander Weir, **Richard E. Balzhiser**, Robert. H. Kadlec, Chiao-min Chu (electrical engineering), and, above all, **Cedomir M. Sliepcevich**, also greatly contributed to the expansion of my horizons at that stage.

My research career began in 1948, a fortuitous time when funding was readily available, partly from industrial fellowships, partly from grants and graduate-student fellowships from the National Science Foundation (a legacy of Vannevar Bush, the first recipient of this award), but mostly in the form of contracts with various agencies of the U.S. Department of Defense. At that time, very few restrictions were imposed on the details of the subject matter. This freedom enticed me to undertake research on a wide variety of topics, the scope of which frequently expanded as we abandoned our original objectives to pursue experimentally observed anomalies. That practice had several consequences—both negative and positive. A possible negative consequence was, as my departmental chairman warned, that if I persisted in diverse work rather than becoming an acknowledged expert on a particular topic I might never gain national recognition, and perhaps not even tenure. By that time, however, I had become addicted to exploratory research, and I did not heed his advice. A positive consequence of this diversity is that I have played a small role in an engineering aspect of solutions to most major societal problems of the last half-century. As new areas of research emerge, they require the study of new science and technology on the teacher's part as well as the graduate student's part. For example, the beginning of my career as a faculty member coincided with the initial appearance of large electronic digital computers. As a direct result, most of my research has involved the numerical solution of increasingly complex models, the development of required new algorithms, and confirmatory experimental work—a requirement I have always imposed on modeling.

My time for teaching and research at Michigan was gradually usurped by administrative duties, and the offer of a chair at the University of Pennsylvania that would permit me to devote all of my efforts to preferred activities prompted me to leave Michigan. That promise materialized under the leadership of **Arthur E. Humphrey**, Joseph Bordogna, and **Eduardo Glandt**, although, with my consent, it was occasionally violated. I was then (35 years ago), and am now, grateful for the acceptance and support of my colleagues at Penn.

One of the greatest rewards of an academic career is the opportunity to work with and learn with graduate students. It has been my good fortune to collaborate with a continual series of truly exceptional students who were attracted by the opportunity to work on problems of obvious importance to our society and were willing to share the risks of exploratory research and accept the burden of carrying out both numerical and experimental work. Because of our close intellectual interactions and the bonds of trust that developed, they have become my second family. I will mention only four by name, **J. David Hellums** and **Lawrence B. Evans**, who are here today, Warren D. Seider, with whom I have interacted almost every day for 40 years, and Hiroyuki Ozoe, with whom I have continued to collaborate during the entire 30 years since he returned to Japan.

My wife Renate has been not only supportive and inspiring, but also, by virtue of her editorship of *International Chemical Engineering*, has also encouraged me to seek out literature in other languages. As a consequence, *Verein Deutscher Ingenieure* made me a corresponding member, presumably in appreciation for my calling attention to the overlooked German literature in chemical engineering. In the last several years I have had a very gratifying, perhaps unique, privilege. My grandson, Stefan C. Zajic, while an undergraduate, collaborated with me in research and became a co-author of several publications.

Considering the very low public profile of engineering, it is surprising that anyone chooses to study engineering. Yet every autumn, all over the country, remarkable young people show up in our classrooms for that purpose. In general, they are brighter, better prepared, more analytical, more motivated, more self-disciplined, and have a higher order of integrity than their counterparts in other fields. They are clearly deserving of the experience and benefits of an engineering education. As teachers and employers, we should recognize and appreciate this bounty, and, considering their initial talent, we should not take too much credit for their later achievements.

Sixty years into my professional career, I consider myself fortunate and privileged to have had the experiences and benefits of an engineering education, not just in the formal sense, but also by virtue of the lifelong process I have described. I am cognizant of and grateful for the contributions of my colleagues and collaborators to my career. Finally, I am very proud to be an engineer, to be a member of the National Academy of Engineering, and to receive the Founders Award.

Call for Nominations for 2003–2004 NAE Awards

DRAPER • RUSS GORDON • FOUNDERS • BUECHE
NAE AWARDS

For the past 40 years, NAE has recognized outstanding engineers for the development of (or involvement in) engineering innovations or processes that have greatly improved people's lives. NAE awards five prizes and bestows more than $1.5 million biennially for achievements in engineering and engineering education. We invite you to help us continue this tradition by nominating outstanding engineers for the next round of prizes.

The Founders Award and Arthur M. Bueche Award are presented annually at the NAE Annual Meeting. The Charles Stark Draper Prize is awarded annually in February during National Engineers Week. The Bernard M. Gordon Prize (even numbered years) and the Fritz J. and Dolores H. Russ Prize (odd numbered years) are awarded biennially. Nominees for the 2004 Draper and Gordon prizes and the 2003 Founders and Bueche awards will be accepted from January 3, 2003, through April 7, 2003. Members and foreign associates will receive nomination materials by mail. Please note: Nominations for the 2005 Russ Prize will be accepted in January 2004.

Nonmembers who wish to submit nominations can obtain materials from Kimberly West at (202) 334-1628 or *kwest@nae.edu*. Information may also be downloaded from our website *www.nae.edu/awards*. Nominations must be mailed or faxed to: NAE Awards, National Academy of Engineering, 500 Fifth Street, N.W., NAS 316, Washington, DC 20001. Fax: (202) 334-1595.

Norman Fortenberry Named Director of New Education Center

Norman L. Fortenberry

Norman L. Fortenberry has been named director of the Center for the Advancement of Scholarship on Engineering Education (CASEE), a new NAE initiative to catalyze improvements in engineering education by focusing attention on what is being taught and how it is being taught.

CASEE is the final part of a four-part strategy to improve the effectiveness of engineering education. The other components of the strategy were already initiated:

- In 1999, the Committee on Engineering Education was established as a standing program of the Office of the President of NAE. The committee studies issues related to engineering education through projects that explore timely questions.
- In 2000, the NAE Council expanded its interpretation of the criteria for NAE membership to recognize contributions to engineering education.
- In 2001, the Bernard M. Gordon Prize for Innovation in Engineering and Technology Education was established as a biennial award of $500,000 to emphasize the importance of education to the future of engineering.

Dr. Fortenberry most recently served as senior advisor for policy, analysis, and planning, as well as acting division director for undergraduate education in the Directorate for Education and Human Resources of the National Science Foundation (NSF). Dr. Fortenberry has served in multiple capacities at NSF over a 10-year period and is the only person to have served concurrently as director of two separate divisions for a two-year period. Prior to joining NSF, Dr. Fortenberry was a faculty member in mechanical engineering at Florida A&M University. He also served as executive director of the GEM Consortium, an alliance of universities and employers devoted to promoting engineering and science education . Dr. Fortenberry can be reached by e-mail at *nfortenb@nae.edu* or by telephone at (202) 334-1926.

Grant Support for *EngineerGirl!* Website

NAE recently received a $35,000 grant from the Northrop Grumman Litton Foundation to support an NAE intern dedicated to developing new educational content for the *EngineerGirl!* website. In 1998, NAE launched the *Celebration of Women in Engineering* website to provide information and inspire girls to pursue careers in engineering. Over a two-year period, the site was renamed *EngineerGirl!* and completely redesigned to appeal to young women in grades 6 through 12 and the adults who support them (parents, teachers, counselors, club leaders, and engineers).

Sixteen girls from 14 states and Canada were recruited to help create the new site by suggesting content and providing feedback on the design. Features of the site include the "Gallery of Women Engineers," "Ask an Engineer," detailed career descriptions, engineering "Fun Facts" (e.g., a woman supervised the construction of the Brooklyn Bridge), and a growing number of educational links related to engineering and technology.

EngineerGirl!'s fact-based, engineering-related content includes: engaging text and images appropriate to middle school students; links to reviewed resources (both online and traditional media) for students as well as parents and teachers; career descriptions and role models in the "Gallery of Women Engineers"; material connecting *EngineerGirl!* content to various areas of the middle and high school curriculum. The site was visited by more than 50,000 users in the first year; it currently receives almost 800 visits a day.

EngineerGirl! has been publicized through National Engineers Week, the Girl Scouts, the Society of Women Engineers, the Women in Engineering Programs and Advocates Network, and teacher organizations. This fall, in partnership with the International Technology Education Association, NAE publicized *EngineerGirl!* in the October issue of *The Technology Teacher* magazine.

The grant from Northrop Grumman Litton will be used to support a graduate student who will be selected through the existing National Academies Internship Program, which brings high potential science and engineering students to Washington, D.C. While working at NAE, the intern will develop new website content and participate in outreach activities, which will include visiting classrooms and making presentations at engineering and teacher conferences.

The *EngineerGirl!* website was created through a grant from the AT&T Foundation and is currently supported by Texas Utilities and Southern Company. The goal is to make the *Celebration of Women in Engineering/EngineerGirl!* website the premier web portal for information about engineering careers specifically designed for girls.

Steve Meyer Interns at NAE

Steve Meyer

Steve Meyer, a master's degree candidate in technology education at the University of Wisconsin-Stout, Menomonie, and an intern at NAE since September, has been working with Greg Pearson on the Technological Literacy Assessment Project. Meyer, who earned a bachelor's degree in physics from Luther College, Decorah, Iowa, has a broad-based education in mathematics, the sciences, and technology. He believes very strongly in technological literacy for everyone. In his career so far, he has been involved in technology issues at the local, state, and national levels. For the past two years, Steve has been teaching technology education—as well as coaching football and track—at Nekoosa High School, Nekoosa, Wisconsin. In January 2003, he will begin teaching technology education at the University of Wisconsin-Stout. Meyer also has a consulting company, Technological Literacy Consulting (TLC), that specializes in educational consulting and public speaking. He can be reached at *meyerste@post.uwstout.edu*.

Assessing Technological Literacy

NAE, in partnership with the National Research Council Board on Testing and Assessment, is launching a new study on assessing technological literacy in the United States. The study, which will be chaired by NAE Member **Elsa M. Garmire**, Dartmouth College, is a follow-on study to the work done by the Committee on Technological Literacy, which last January published *Technically Speaking: Why All Americans Need to Know More About Technology*. (See the companion website, *www.nae.edu/techlit*, for more information.) One of the findings of the earlier project was that we have few data to indicate the extent and nature of what Americans understand about the technological world. The new project, funded by the National Science Foundation, is intended to provide guidance to public-sector and private-sector test developers on how to measure technological literacy in three populations: students, teachers, and out-of-school adults. The first meeting of the Committee on Assessing Technological Literacy is scheduled for January 16–17, 2003, at the National Academies. For more information, contact Greg Pearson, program officer, (202) 334-2282 or *gpearson@nae.edu*.

Message from the Foreign Secretary

Harold K. Forsen

The annual meeting of the International Council of Academies of Engineering and Technological Sciences (CAETS) took place at the Czech Technical University in Prague, Czech Republic, August 26–27, 2002. Twenty of the 26 member academies attended; visiting representatives of academies of engineering in Russia, Slovakia, and South Africa also attended. Members of the newly elected 2002–2003 Board of Directors include the Czech Republic, Finland, Hungary, India, Korea, Mexico, and the United States; NAE President **Bill Wulf** became president of CAETS for 2003. No new academies have as yet applied for membership to CAETS, but the presence of the visiting representatives was encouraging. Further details will become available on the CAETS website (*http://www.CAETS.org*).

Following the CAETS meeting, NAE foreign associates and members met in Stuttgart, Germany. Some 29 foreign associates from as far away as China and Japan attended, along with Europeans from Austria, Belgium, Germany, Italy, the Netherlands, Sweden, Switzerland, and the United Kingdom. Two NAE members who were visiting in Europe also attended. The meeting was hosted by DaimlerChrysler and foreign associate **Wolfgang Schmidt**. President Bill Wulf and I made short presentations on current NAE activities. Attendees showed considerable interest in our counterterrorism activities. Later we toured the Mercedes assembly factory near Stuttgart. Everyone seemed to enjoy the meeting thoroughly, and we are looking for potential hosts in other European countries so we can have meetings more often.

Eight new foreign associates were inducted at the NAE Annual Meeting, one a carryover from last year. Unfortunately, only a few of them were able to remain for the Foreign Associates' Breakfast, to which all attending foreign associates are invited. At the breakfast, foreign associates had an opportunity to meet with new and former colleagues and discuss issues important to the profession, their countries, and the Academy. NAE President Bill Wulf and Executive Officer **Lance Davis** and Bill Colglazier and John Boright of the National Research Council (NRC) also attended. I encourage all of our foreign associates to attend the NAE Annual Meeting, and especially to take advantage of this get-together to exchange views on topics of international interest.

The second Japan-America Frontiers of Engineering (JAFOE) was held in Tokyo on October 23–26, 2002, at the National Museum of Emerging Science and Innovation (MeSci), a science center sponsored by the Japan Science and

Technology Corporation, which also sponsored the symposium. Sixty-two young investigators were invited from the two countries; guests representing CAETS academies in Australia, China, and India also attended. The sessions were interspersed with visits to MeSci and the Superconductivity Research Laboratory. Poster sessions provided additional opportunities for attendees to present some of their research data and publications. Ample time was provided for attendees to discuss their research and other areas of common interest and to learn about the culture of the host country. (For a more detailed description of the JAFOE Symposium, see p. 48.) A planning session was held to discuss the agenda and schedule for the next JAFOE symposium, which will be held in the United States at the Beckman Center on November 20–22, 2003.

While in Japan, President Bill Wulf, Executive Officer Lance Davis, and I were honored to meet with foreign associates in the area, courtesy of our host, the NEC Corporation, and its chairman and NAE foreign associate **Hajime Sasaki**. The meeting was held at the NEC Central Research Laboratory on the Monday following the JAFOE meeting and was attended by eight local foreign associates and NAE member **Nicky Lu** from Taiwan. The program included an overview of the NEC laboratory and a tour of some exciting new developments. President Wulf and I described some of NAE program activities, and attendees asked many questions and offered some suggestions for future consideration. The foreign associates expressed great interest in having more of these meetings, and we agreed that we would look into having more meetings, generally in conjunction with travel for JAFOE and German-American Frontiers of Engineering (GAFOE) meetings. Because the NAE delegation had to stay over Sunday, NEC graciously provided us with a tour of the Hakone region south of Tokyo, where we were able to view the splendor of Mt. Fuji and Lake Ashinoko.

The Committee on International Programs (CIP) of the NRC, which reports to the Governing Board, is made up of the foreign secretaries of the NAE, National Academy of Sciences, and Institute of Medicine. The committee recently met to begin developing a strategic plan for the committee and for our international programs with an eye toward increasing the international presence of the National Academies. We developed a three-dimensional matrix in areas where regional programs and interest already exist, collected a list of possible activities, and considered possible external sources of funding. The next step is for the five unrepresented NRC divisions to contribute their ideas and participate in planning activities with representatives to the CIP. We also plan to have presidential fellows for international programs join us as part of the CIP. We are still developing the position description of these senior fellows, but it is hoped they will provide guidance and contacts at high levels with international organizations and sponsors. We identified three principles (or banners) for our international activities: Capacity Building for the Use of Science to Inform Policy and Policy to Develop Science; Global Health and Environment: Toward a Sustainable World; and International Security: Toward a Safer World.

Much remains to be done, but we feel we have made a good start. Additional resources are being made available for us to develop and execute these programs, and we will be working with NRC divisions and our International Advisory Board to flesh out the plan.

Harold K. Forsen
Foreign Secretary

NAE Newsmakers

Zdenek P. Bazant, W.P. Murphy Professor of Civil Engineering and Materials Science, Northwestern University, has been elected a member of the **National Academy of Sciences**, the **Austrian Academy of Sciences**, and the **Istituto Lombardo Academia di Scienze e Lettere**. In addition, Dr. Bazant received **honorary doctorates** from **University of Colorado, Boulder**, and **Politecnico di Milano, Italy**. He was also named a "Highly Cited Scientist" by the Institute of Scientific Information. This award is given to the 250 authors most often cited worldwide in all fields of engineering.

Robert G. Bea, professor of civil and environmental engineering, University of California, Berkeley, was awarded the **ASCE Ralph Peck Medal**. Dr. Bea was honored for his pioneering contributions to the design of pile foundations for offshore platforms and the application of reliability methods to the design of deep foundations.

Arthur E. Bergles, Clark and Crossan Professor of Engineering, Emeritus, Rensselaer Polytechnic Institute, received the **Itherm Achievement Award** from the Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems. Dr. Bergles was also presented with the **Holladay Distinguished Fellow Award** from ASHRAE for his continuing preeminence in engineering and research. In addition, Dr. Bergles was awarded the 2002 **International SFT Award** from the French Thermal Society for his contributions to thermal sciences and international cooperation.

John E. Breen, Nasser I. Al-Rashid Chair in Civil Engineering, University of Texas, received the 2002 **Freyssinet Medal** from the Fédération Internationale de Béton. Dr. Breen was cited "for his major contributions to the development of clear conceptual thinking in the design of concrete structures." He was also acknowledged "for his many important contributions to the development of transparent design codes for both concrete buildings and bridges" and "his numerous stimulating lectures on the design and application of structural concrete given worldwide."

On January 29, 2003, **Edward J. Cording**, professor of civil engineering, University of Illinois at Urbana-Champaign, will receive the **Nonmember Award for Outstanding Achievement in Construction**, and **George J. Tamaro**, senior partner of Mueser Rutledge Consulting Engineers, will receive the **Member Award for Outstanding Achievement in Construction** from the Moles. These awards are considered by many to be the most prestigious awards in the construction industry.

Charles Elachi, director, Jet Propulsion Laboratory, was selected as co-recipient of the **2002 Techno-Entrepreneurial Achievement for the World Environmental Well-Being Award**. Given by the Takeda Foundation, this award is presented to individuals who have made outstanding contributions to the creation and application of new knowledge in three fields: social/economic well-being (information and electronics), individual/humanity well-being (the life sciences), and world environmental well-being.

Samuel C. Florman, chairman, Kreisler Borg Florman Construction Company, was presented with the **2002 Civil Engineering History and Heritage Award**. Presented by ASCE, the award is given to individuals who have made outstanding contributions to a better understanding of, and appreciation for, the history and heritage of civil engineering.

In recognition of his seminal contributions to mineral processing science and engineering and to Australian mineral processing research and innovation, **Douglas W. Fuerstenau**, professor in the Graduate School, University of California, Berkeley, was recently elected a **Foreign Fellow** of the **Australian Academy of Technological Sciences and Engineering**.

Elias P. Gyftopoulos, professor emeritus, Massachusetts Institute of Technology, was awarded the **2002 ASME Robert Henry Thurston Award**. Dr. Gyftopoulos was cited for publishing significant scholarly books and articles that represent landmark contributions to thermodynamics and related physical sciences.

Michel T. Halbouty, chairman and chief executive officer, Michel T. Halbouty Energy Company, was awarded the **Gold Medal for Distinguished Achievement** by the American Petroleum Institute. Mr. Halbouty was recognized for his many contributions to the industry, geology, petroleum engineering, and the welfare of the nation.

John W. Hutchinson, Gordon McKay Professor of Applied Mechanics, Harvard University, was awarded the 2002 **ASME**

Timoshenko Medal. Dr. Hutchinson was recognized for seminal contributions to our understanding of the mechanical behavior and failure of materials and structures.

Sia Nemat-Nasser, professor, Center of Excellence for Advanced Materials, Department of Mechanical and Aerospace Engineering, University of California, San Diego, was awarded the 2002 **ASME Nadai Medal**. Dr. Nemat-Nasser was cited for his outstanding theoretical and experimental research on a wide range of material systems and investigations into various phenomena.

Robert M. Nerem, Parker H. Petit Professor and director, Institute for Bioengineering and Bioscience, Georgia Institute of Technology, was presented with the 2002 **Pierre Galletti Award** at the AIMBE annual meeting. Dr. Nerem was recognized for his contribution to public awareness of medical and biological engineering and to the promotion of the national interest in science, engineering, and education.

Norman R. Scott, professor, Department of Agricultural and Biological Engineering, Cornell University, was awarded the 2002 **Cyrus Hall McCormick-Jerome Increase Case Gold Medal Award**. Dr. Scott was recognized for his outstanding accomplishments as an administrator and as the leader of an engineering society.

Robert H. Wagoner, George R. Smith Chair in Engineering, Ohio State University, has been selected to receive the 2003 **Fellow Award of the Mineral, Metals and Materials Society**. The award is given for outstanding contributions to the practice of metallurgy or materials science and technology.

Eugene Wong, professor emeritus, University of California, Berkeley, has been elected a foreign member of the **Royal Swedish Academy of Engineering**.

Wm. A. Wulf, president, National Academy of Engineering, was presented with the **University of Pennsylvania Medal for Distinguished Service** during a ceremony celebrating the sesquicentennial of Penn engineering. Dr. Wulf was the keynote speaker at the event.

In Memoriam

PIERRE R. AIGRAIN, 78, consulting engineer, died on October 30, 2002. Dr. Aigrain was elected a foreign associate to NAE in 1976 for contributions to solid-state devices and to science and technology policies in France.

JOHN D. FERRY, 90, professor emeritus of chemistry, University of Wisconsin-Madison, died on October 18, 2002. Dr. Ferry was elected to NAE in 1992 for developing experimental techniques and a conceptual framework for modern viscoelasticity of polymers.

JOSEPH E. ROWE, 75, retired associate vice president for research and retired director, Research Institute, University of Dayton, died on October 23, 2002. Dr. Rowe was elected to NAE in 1977 for contributions to the theory and design of high-power microwave electron tubes and solid-state microwave devices.

VIVIEN T. STANNETT, 85, professor emeritus of chemical engineering, North Carolina State University, died on October 1, 2002. Dr. Stannett was elected to NAE in 1995 for contributions to the understanding of transport processes and polymer radiation chemistry in polymers.

CHANG-LIN TIEN, 67, University Professor and NEC Distinguished Professor of Engineering, University of California, Berkeley, died on October 29, 2002. Dr. Tien was elected to NAE in 1976 for contributions to the theory of heat transfer and for its application to difficult contemporary engineering problems.

KEITH W. UNCAPHER, 80, senior vice president, Corporation for National Research Initiatives, died on October 10, 2002. Mr. Uncapher was elected to NAE in 1998 for his work on information technology on the national level.

Calendar of Meetings and Events

2003

January 13–14	NAE/IOM Committee on Engineering and the Health Care System Meeting
January 14–15	Intel LEAP Conference
January 15	NRC Governing Board Executive Committee Meeting
January 16–17	NAE/NRC Committee on Assessing Technological Literacy Meeting
January 23	NAE Peer Committee Chairs Workshop
January 28	NAE Finance and Budget Committee Conference Call
January 30	NAE Membership Policy Committee Meeting Irvine, California
February 3	Beckman Center Advisory Board Meeting Irvine, California
February 3–4	NRC Governing Board Meeting Irvine, California
February 4	The National Academies Corporation (TNAC) Board of Directors Meeting Irvine, California
	NAE/NAS/TNAC Dinner Irvine, California
February 5	NAE/NAS Officers Meeting and Joint Council Meeting Irvine, California
February 5–6	NAE Council Meeting Irvine, California
February 6	NAE National Meeting Irvine, California
February 6–7	NAE/IOM Engineering and the Health Care System Workshop Irvine, California
February 18	NAE Draper and Russ Prizes Press Conference National Press Club, Washington, D.C.
	NAE Draper and Russ Prizes Forum
	NAE Draper and Russ Prizes Dinner and Presentation Ceremony Union Station, Washington, D.C.
February 20	NRC Governing Board Executive Committee Meeting
March 10–11	NAE/IOM Engineering and the Health Care System Workshop
March 13	NAE Regional Meeting Seattle, Washington
March 18	NRC Governing Board Executive Committee Meeting
April 3	NAE Regional Meeting Troy, New York
April 8	NAE Regional Meeting Urbana, Illinois
April 10	NAE Regional Meeting Boulder, Colorado
April 15	NRC Governing Board Executive Committee Meeting
April 26–29	NAS 2003 Annual Meeting
April 28	NAE Finance and Budget Committee Conference Call
April 28–29	NAE/IOM Committee on Engineering and the Health Care System Meeting
May 1–3	German-American Frontiers of Engineering Symposium Ludwigsberg, Germany
May 5–6	NAE Convocation of Professional Engineering Societies
May 8	NAE Regional Meeting Cambridge, Massachusetts

All meetings are held in one of the National Academies buildings, Washington, D.C., unless otherwise noted. For information about regional meetings, please contact Karen Spaulding at *kspaulding@nae.edu* or (202) 334-2197.

The National Academies Update

National Academies Presidents' Statement on Science and Security

On October 18, 2002, NAE President **Wm. A. Wulf**, *National Academy of Sciences President Bruce Alberts, and Institute of Medicine President Harvey Fineberg issued the following "Statement on Science and Security in an Age of Terrorism":*

After the September 11, 2001, assaults on the World Trade Center and the Pentagon, and the subsequent anthrax attacks via the postal system, the scientific, engineering, and health research community was quick to respond at many levels, from initiating new research to analyzing needs for improved security. This community recognizes that it has a clear responsibility to protect the United States, as it has in the past, by harnessing the best science and technology to help counter terrorism and other national security threats.

In meeting this responsibility, the scientific, engineering, and health research community also recognizes a need to achieve an appropriate balance between scientific openness and restrictions on public information. Restrictions are clearly needed to safeguard strategic secrets; but openness also is needed to accelerate the progress of technical knowledge and enhance the nation's understanding of potential threats.

A successful balance between these two needs—security and openness—demands clarity in the distinctions between classified and unclassified research. We believe it to be essential that these distinctions not include poorly defined categories of "sensitive but unclassified" information that do not provide precise guidance on what information should be restricted from public access. Experience shows that vague criteria of this kind generate deep uncertainties among both scientists and officials responsible for enforcing regulations. The inevitable effect is to stifle scientific creativity and to weaken national security.

To develop sharp criteria for determining when to classify and/or restrict public access to scientific information, as well as to address the other important issues outlined below, we call for a renewed dialogue among scientists, engineers, health researchers and policy makers. To stimulate such a dialogue, we present two "action points": one focused on scientists, engineers, and health researchers and the other focused on policy makers.

Action Point 1

The scientific, engineering, and health research community should work closely with the federal government to determine which research may be related to possible new security threats and to develop principles for researchers in each field. Among the questions that the scientific, engineering, and health community should address are the following:

- Are there areas of currently unclassified research that should be classified in the new security environment?
- How can the scientific, engineering, and health community establish systems that can monitor this issue effectively, as science and potential threats change over time?
- Do any materials widely used in research require additional security procedures?
- How can the scientific, engineering, and health community establish systems that will rapidly detect new potential threats from terrorism, as well as novel opportunities for countering terrorism, that arise from new discoveries, and convey these in an effective manner to the relevant government agencies?

Action Point 2

The federal government should affirm and maintain the general principle of National Security Decision Directive 189, issued in 1985:

> *No restrictions may be placed upon the conduct or reporting of federally funded fundamental research that has not received national security classification, except as provided in applicable U.S. statutes.*

In determining what research and information should be restricted from public access, agencies should ask:

- How should we apply the principle of building "high fences around narrow areas" in the new security environment, so as to protect critical and well-defined information and yet permit the essential flow of scientific and technical knowledge and human capital?

- How can such determinations be made at the outset of a research program so as not to disrupt the research?
- How can we avoid creation of vague and poorly defined categories of "sensitive but unclassified" information that do not provide precise guidance on what information should be restricted from public access?
- How can the government enlist the help of a large number of the nation's best scientists, engineers, and health researchers in counterterrorism efforts, for both the unclassified and the classified areas of the overall program?

Achieving the purpose of scientific and technological activity—to promote the welfare of society and to strengthen national security—will require ingenuity from our science, engineering, and health community, as well as from the many agencies of the federal, state, and local governments involved in counterterrorism. The nation's safety and the continued improvement of our standard of living depend on careful, informed action on the part of both governments and the scientific, engineering, and health community. A continuing, meaningful dialogue needs to begin—one that produces a true collaboration for the many decisions that need to be made.

Everglades Restoration Plan

A central feature of the complex effort to restore the Florida Everglades is a proposal to drill more than 300 wells that would funnel up to 1.7 billion gallons of water a day into underground aquifers, where the water will be stored and then pumped back to the surface to replenish the ecosystem during dry periods. Aquifer storage and recovery, as the process is known, has been successfully employed on a much smaller scale in Florida since 1983, but the size of the new proposal is unprecedented and has raised several concerns. For example, how much of the surface water stored in aquifers can actually be recovered? And what if fresh surface water mixes with salt water or undergoes other undesirable chemical changes while underground?

To answer these questions, federal and state officials working on the Everglades restoration project have drafted a comprehensive research plan that "goes a long way to providing the needed information," according to a new report from the National Research Council (NRC). The research plan clearly responds to suggestions from scientists in Florida and in a previous NRC report. It also acknowledges the importance of conducting pilot studies on a regional scale to determine the consequences of large-scale aquifer storage and recovery.

The committee that wrote the new report, *Regional Issues in Aquifer Storage and Recovery for Everglades Restoration*, commended the authors of the Everglades research plan for designing studies that will attempt to compile all existing data, map the architecture of the aquifers and underground water flows, measure salinity, and test for the presence of chemicals and pathogens. The additional monitoring proposed in the research plan for the pilot sites is a good first step, the committee said; but more test wells are needed, as well as more extensive monitoring, because the salinity and physical properties of the water being recovered is likely to vary considerably from site to site. Everglades researchers also should study the effects of chemicals and pathogens on ecosystem communities and not just on individual organisms, so that the findings can help meet the objectives of the overall Everglades restoration plan.

Some of the funds currently allocated for coring could be diverted for more test wells and monitoring. Coring, which uses drills to pull up cylinders of rock samples, can be useful, the committee said, but it is costly, and it may yield unreliable and nonrepresentative data.

The most important overall improvement to the research plan at this point would be greater attention to the principle of adaptive management, the committee said. The adaptive management approach allows natural-resource managers to examine the results of incremental planning steps or experiments and adapt subsequent decisions accordingly. Planners should consider now what should be done if the Everglades studies show that aquifer storage and recovery on the proposed scale is not feasible.

NAE member **Daniel P. Loucks**, Cornell University, served on the committee that reviewed the plan. The full text of the report is available online at: *http://www.nap.edu/catalog/10521.html*.

Publications of Interest

The following reports were recently published by the National Academy of Engineering or the National Research Council. Unless otherwise noted, all publications are for sale (prepaid) from the National Academies Press (NAP), 500 Fifth Street, 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 (888) 624-8373. *(Note: Prices 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 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.)*

Florida Bay Research Programs and Their Relation to the Comprehensive Everglades Restoration Plan. Florida Bay is closely linked to the Everglades through a series of canals and waterways. In the late 1980s, the crystal-clear water in the bay began to cloud up, and dense meadows of seagrasses began to disappear. It was expected that the Comprehensive Everglades Restoration Plan (CERP) would help reverse these conditions. However, recent observations suggest that the influx of fresh water planned by CERP might actually promote these changes in the marine environment. The report suggests that a focused technical review and evaluation be carried out and that research be conducted to reduce uncertainties about the potential long-term effects of CERP on Florida Bay and to allow time for the development of alternative strategies if necessary. Paper, $18.00.

In War and Peace: My Life in Science and Technology. This thoughtful and candid memoir by Guy Stever, NAE/NAS member and NAE foreign secretary from 1984–1988, recounts his experiences during World War II when he worked with the British to develop and refine radar technology, his involvement in the antiballistic missile defense program, and his participation in the establishment of new institutions, including NASA. Stever, who has achieved a position of world leadership in science and technology, offers remarkable insights into the history of the last half-century. Hardbound, $29.95.

Making the Nation Safer: The Role of Science and Technology in Countering Terrorism. The openness and efficiency of our key infrastructures make them susceptible to terrorist attacks. This report examines areas of vulnerability to nuclear and radiological threats, bioterrorism, public health threats, toxic chemicals, and attacks on information, energy, and transportation systems. Technical approaches to mitigating these threats are presented. Paper, $43.95.

Privatization of Water Services in the United States: An Assessment of Issues and Experience. Many communities in the United States are looking into the advisability of privatizing water and wastewater services as a way of reducing costs and improving efficiency. This report evaluates the fiscal and policy implications of privatization, describes scenarios in which it works best, and enumerates the efficiencies that might be gained by contracting with private water utilities. Hardcover, $39.95.

Seventh Annual Symposium on Frontiers of Engineering. This collection includes summaries of presentations given at the March 2002 symposium. Topics include: micromechanical flyers, dynamic planning and control of civil infrastructure systems, the design of future wireless systems, and reengineering the paralyzed nervous system. Paper, $31.00.

Small Wonders, Endless Frontiers: A Review of the National Nanotechnology Initiative. Carried out at the request of the White House Economic Council and other federal agencies, this review recommends that support be increased for the National Nanotechnology Initiative long-term research program and that interdisciplinary efforts be promoted. Although the report recognizes that nanotechnology has the potential to revolutionize industry, it recommends further study of the basic scientific principles of nanotechnology and a more widespread interdisciplinary culture. The report concludes that continued investment in the development of nanotechnological instruments, as well as continued collaboration at the local, national, and international level, are necessary. Paper, $18.00.

An Assessment of Precision Time and Time-Interval Science and Technology. Precision time and time-interval (PTTI) science and technology are used by all of the armed services for navigation and communications. Military operations that depend on PTTI that could benefit from improvements in PTTI technology include weapon-system four-dimensional coordination, network-centric warfare, and secure military communications. Research areas related to PTTI that would lead to improved military capabilities include materials science, chemistry, and atomic, molecular, and optical physics. The report presents the committee's analysis of the current status of PTTI in the United States and findings and recommendations based on that analysis. Paper, $18.00.

Evolutionary and Revolutionary Technologies for Mining. The United States is a major producer of metals and other mined products, and mining is very important to our economy. The industry is in transition, however, because of environmental considerations, poorer grades of ore, regulatory burdens, and limited access to land. Under these circumstances, innovation and development are more important than ever. The National Research Council was asked to provide guidance on future technological developments in the mining sector. This report identifies research areas for new technologies in exploration, mining and processing, and associated health, safety, and environmental issues. The report calls for more cooperation between government, industry, and academia in mineral research and development and emphasizes the essential role of the federal government in supporting research and advanced education. Paper, $25.00.

For Greener Skies: Reducing Environmental Impacts of Aviation. Although each generation of commercial aircraft produces less noise and fewer emissions, the demand for commercial air transportation services has grown so quickly that *total* aircraft noise and emissions have continued to increase. Meanwhile, noise and air quality standards have become more stringent, making it increasingly difficult for airlines to reconcile public demand for air services with concurrent demands to reduce noise, improve air quality, and protect the environment. The Federal Aviation Administration (FAA), the National Aeronautics and Space Administration (NASA), and the Environmental Protection Agency (EPA) asked the National Research Council to recommend research strategies and approaches that could mitigate the environmental effects of aviation. Based on the roles and missions of the FAA, NASA, and EPA, this report provides a framework for government research policies and programs that could lead to technological change fast enough for commercial aviation to grow and still be environmentally sustainable.

National Security and Homeland Defense: Challenges for the Chemical Sciences in the 21st Century. This report of the proceedings of the National Security and Homeland Defense Workshop focuses on research in chemistry and chemical engineering. The workshop addresses four themes: discovery, interfaces, challenges, and infrastructure. The committee used the workshop findings to identify "grand challenges" for enlisting advances in the chemical sciences in the counterterrorism effort. Each grand challenge includes specific challenges and related research needs. The goals of the report are to help chemical scientists understand how their research can be applied to national security problems, to suggest ways to improve the safety of U.S. civilians and military personnel, and to provide information to federal agencies to support investments in research that can contribute to national security. Paper, $28.25.

Naval Engineering: Alternative Approaches for Organizing Cooperative Research—Special Report 266. A key responsibility of the Office of Naval Research (ONR) is to maintain a robust capability in naval engineering and improve the Navy's ability to translate creative research into innovative warships. However, the Navy is facing a diminishing knowledge base and a serious shortage of personnel with broad, interdisciplinary experience. To address these problems, the Transportation Research Board was asked to investigate and evaluate alternative approaches for structuring cooperative research programs in naval engineering. The report describes the basic organizational concepts of four models and identifies the advantages and disadvantages of each. It also identifies the features of each model that would satisfy ONR's objectives of revitalizing the field of naval engineering and improving the design and production of naval ships. Paper, $20.00. Available from TRB Bookstore at (202) 334-3213 or online at *http://www.nationalacademies.org/trb/bookstore/*.

Regulation of Weights, Lengths, and Widths of Commercial Motor Vehicles—Special Report 267. In the 1998 Transportation Equity Act for the 21st Century, the secretary of transportation is instructed to ask the Transportation Research Board to conduct a study of the regulations governing the weights, lengths, and widths of commercial motor vehicles operating on highways subject to federal regulation and to recommend revisions to the regulations, if appropriate. Federal regulations affect the costs of transporting freight and passengers. The report recommends organizational arrangements that would promote changes in the regulations to improve the efficiency of truck freight transportation and mitigate the costs of truck traffic to the public. The committee's recommendations relate primarily to the process by which federal regulations are established and the relationship between the federal government and state governments in regulating truck size and weight. Paper, $24.00. Available from TRB Bookstore at (202) 334-3213 or online at *http://www.nationalacademies.org/trb/bookstore/*.

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