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The BRIDGE

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Editor-in-Chief

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Editorial

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

There's Work to Be Done

As the beginning of the new millennium nears, it is sobering to take stock of the challenges facing our society that require the deep involvement of engineers.

We approach the millennium with a justifiable pride in the enormous achievements of engineering. In the last century alone, these achievements have revolutionized our lives and changed the physiognomy of our cities. From automobiles and aviation to travels in space, from telephony and radio to television and computers, and from water supply and sanitation to bioengineering, they have changed the ways we work and have nearly doubled our life expectancy. There will be ever more demands for engineering to extend those achievements and the reach of human beings far beyond where we are today. But, as we approach the end of this century, we need to recognize that much needs to be done to continue on the high road of innovation and that there are new kinds of challenges to be addressed.

Many of these challenges are of a purely technical nature, like finding ways to remain competitive by building better, faster, and cheaper, to go beyond the limits of silicon chips and invent entirely new kinds of computing elements, to create more sophisticated artificial organs and bio-machine interfaces, to develop the enormous possibilities of nanotechnologies, or to devise protective systems against terrorist attacks.

In the wake of recent events in the Balkans and other humanitarian disasters, it is clear that new kinds of military technologies are called for to deal with diffused, low-technological-intensity adversaries and conflicts, and that new logistic approaches have to be devised for massive humanitarian aid and rapid reconstruction. Here again, the need for creative engineering is paramount, as it is also in the continued development of intelligence systems to help us stay informed about the strength and intentions of potential adversaries.

The list of these technological challenges is a long one. But even longer, perhaps, is that of socio-technological challenges—of how to address problems that require for their solution an intimate combination of technical and social skills. The permanence of poverty in over one-sixth of the world population is one such problem. The need to create jobs for over a billion people in the megacities of the developing world is another. In an ever more populous world, hunger and joblessness are dangerous and destabilizing global problems. Beyond our obvious self-interest in addressing these problems, simple humanity demands that we resolve to conquer them. We now possess the technology to increase food production, to create adequate shelter for all, and to teach useful skills to everyone, but we have to learn to better couple these technological capabilities with societal and organizational innovations. Engineers must press for recognition of the fact that technologies exist today to solve these problems, and that poverty, joblessness, and lack of shelter are not preordained to remain endemic phenomena of human life. Neither is it preordained that we remain victims of most natural disasters like the recent earthquake in Turkey. There is much that technology can do to mitigate their impact, if society is willing, for instance, to formulate and enforce new codes about seismic construction or new rules about floodplain occupancy.

Closer to home, an example of a key and urgent socio-technological problem is technological literacy. Our citizens should have a sense of technology's role in our lives, of how technological decisions are reached, and of the kinds of questions that should be asked about any new technology. We have seen recently in the case of Kosovo how ill equipped the general public was to understand what could realistically be expected of the military technology employed. It is still not sufficiently recognized that technological literacy is essential to preserve and reinforce democracy in any modern country—certainly in a country as dependent on technology as ours. Engineers have a major role to play in the development of technological literacy, because without it, without a knowledgeable electorate, we cannot hope to counter the continual threats to the federal

R&D budget for engineering and the physical sciences.

U.S. engineering itself needs to be more representative of the U.S. population if it is to deal successfully with major socio-technological challenges at home. Although the battle for more women in engineering is being waged encouragingly, we are not gaining much ground when it comes to underrepresented minorities.

Another major socio-technological challenge for U.S. engineers is how to increase the productivity of vast sectors of our economy. We are fortunate that great engineering achievements have made information technology and telecommunications the most dynamic part of our economy. But the successful dynamism of these fields has not been emulated by other industries and the service sector. It is only recently, for instance, that the whole sector of retailing and merchandising, a large sector of our economy, has begun to recognize the significance that technology holds for its future. In the educational sector also, productivity remains a major concern; university tuitions have far outpaced inflation, and, in primary and secondary schools, achievement does not match investment, despite ever-growing expenditures in technology.

Again, here at home, our engineering skills could be used more effectively to help our government in its relations with other countries. This is a multifaceted issue. A simple example has to do with the large number of foreign students who come here to learn engineering and science. We train those students indistinguishably from our own and do little to prepare them for the leadership positions they usually assume when they return home; this is both a challenge for our engineering schools and an opportunity for our country to help develop competent leadership abroad.

The enormous needs of the rapidly growing number of large cities in the developing world offer us still another opportunity. Those very large urban concentrations, with daunting problems ranging from housing to infrastructure to jobs, must be helped to walk on their own feet. By and large, traditional assistance programs have not worked. A novel self-help approach is needed to trigger new attitudes toward innovation. This may require pooling the needs of several cities across national borders to create sufficiently large markets for urban technological innovations, both indigenous and coming from the developed world, that are appropriate for their economies—an example of an exquisitely difficult but crucial socio-technological challenge for the next millennium.

On the threshold of the new millennium, most engineers undoubtedly have their own lists of challenges and opportunities and their own views of the problems crying for engineering involvement. But one thing is clear: the potential demands on the thin line of American engineers—a line made even thinner by the decreasing number of students interested in engineering—are immense.

There's work to be done.

George Bugliarello

Five Worthy Ways to Spend Large Amounts of Money for Research on Environment and Resources

Jesse H. Ausubel

I envision a large, prosperous economy that treads lightly and emits little or nothing.

Jesse H. Ausubel is director of the Program for the Human Environment at the Rockefeller University in New York City. From 1983 to 1989 he served as director of programs for the National Academy of Engineering.

The first decade of my career I carried briefcases for William A. Nierenberg (NAE), Robert M. White (NAE), and other leaders in formulating such major research programs as the World Climate Program and the International Geosphere-Biosphere Program. Working for the National Academies of Sciences and Engineering, I learned how grand programs are born, what they can do, and what they cost. Spurred by an invitation from the San Diego Science & Technology Council and hoping to rally my colleagues, I here tell my top five "worthy ways" to spend large amounts of money for research on environment and resources.[1] My top five span the oceans, land, human health, energy, and transport. All demand teams of engineers and scientists. Let's

1. count all the fish in the sea;
2. verify that the extension of humans into the landscape has begun a "great reversal" and anticipate its extent and implications during the next century;

3. assess national exposure of humans to bad things in the environment;

4. build 5-gigawatt zero-emission power plants the size of a locomotive; and

5. get magnetically levitated trains (maglevs) shooting through evacuated tubes.

These worthy ways cohere in the vision of a large, prosperous economy that treads lightly and emits little or nothing.

Marine Census

In December 1998 for a week I sailed above the Arctic Circle in the Norwegian Sea, precisely counting herring in the dark. Over the decades of the Cold War, Norwegians honed their submarine acoustics, listening for Soviet vessels motoring out of Murmansk. This technology, integrated with others, makes possible the first-ever reliable worldwide Census of Marine Life. I prefer to say "Census of the Fishes," conjuring beautiful images to Everyman. But humanity needs to understand the diversity, distribution, and abundance of squids, jellies, and turtles, too, and so, deferring to accurate colleagues, I call this first worthy way the Census of Marine Life. But let me make the case primarily for fishes.

Many of the world's leading ichthyologists gathered at Scripps Institution of Oceanography in La Jolla, Calif., in March 1997 to consider what is known and knowable about the diversity of marine fishes (Nierenberg, forthcoming). The meeting attendees reported how many species are known in the world's oceans and debated how many might remain undiscovered. Known marine species total about 15,000. The meeting concluded that about 5,000 yet remain undiscovered. I find the prospect of discovering 5,000 fishes a siren call, a call to voyages of discovery in little explored regions of the Indian Ocean, along the deeper reaches of reefs, and in the midwaters and great depths of the open oceans. The adventures of discovery of Cook, Darwin, and the explorers of Linnaeus's century are open to our generation, too.

The urgency to cope with changes in abundance of fish amplifies the adventure of discovery. In August 1998 at the Woods Hole Oceanographic Institution, the concept of the census was advanced at a workshop on the history of fished populations, some 100–200 of the 15,000–20,000 species. The assembled experts estimated that the current fish biomass in intensively exploited fisheries is about one-tenth of that before exploitation (Steele and Schumacher, forthcoming). That is, the fish in seas where commercial fishers do their best to make a living now weigh only 10 percent of the fish they sought in those seas a few decades or hundred years ago.

Diverse observations support this estimate. For example, the diaries of early European settlers describe marvelous fish sizes and abundance off New England in the 1600s. From Scotland to Japan, commercial records document enormous catches with simple equipment during many centuries. Even now, when fishers discover and begin fishing new places, they record easy and abundant catches, for example, of orange roughy on Pacific sea mounts. Also, scientific surveys of fish stocks indicate fewer and fewer spawning fish (mothers), compared to recruits (their offspring). The ratio of spawners to recruits has fallen to 20 percent and even 5 percent of the level when surveys began. A great marine mystery is what has happened to the energy in the ecosystem formerly embodied in the commercial fish.

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These two dramatic numbers, the 5,000 undiscovered fishes and the lost 90 percent of stocks, suggest the value of a much better and continuing description of life in the oceans. So, I propose a worldwide census. The census would describe and explain the diversity, distribution, and abundance of marine life, especially the upper trophic levels (higher levels of the food chain). Preoccupied by possible climatic change and the reservoirs of carbon that influence it, we have tended to assess life in the oceans in gigatons of carbon, neglecting whether the gigatons are in plankton, anchovies, or swordfish. I care what forms the carbon takes.

Three questions encapsulate the purpose of the census. What did live in the oceans? What does live in the oceans? What will live in the oceans? These three questions mean the program would have three components. The first, probably not large or expensive, would reconstruct the history of marine animal populations since human predation became important, say, the past 500 years.

The second and expensive part of the program would answer "What does live in the oceans?" and would involve observations lasting a few years. We would observe the many parts of the oceans where we have so far barely glimpsed the biology, for example, the open oceans and midwaters, and would strengthen efforts by national fisheries agencies that struggle with meager funds, personnel, and equipment to examine areas near shore where many species of commercial import concentrate.

As a maximalist, I hope to see integration and synchronization of technologies, platforms, and approaches. Acoustics are paramount because every fish is a submarine, and acousticians can now interpret tiny noises 100 kilometers away. Optics also can detect much. For example, scanning airborne lasers, known as lidars, now range far, fast, and perhaps as deep as 50 meters. Lidars can also detect inexpensively if their planes are drones. And least expensive of all, smart and hungry, animals are themselves motivated samplers of their environments, and we could know what they sample if we tag them. The benefits of the technologies soar, if integrated. For example, acoustics, optics, and molecular and chemical methods can be combined to identify species reliably from afar.

Acoustics, optics, and molecular and chemical methods can be combined to identify species.

Answering the third question, "What will live in the oceans?," requires the integration and formalization that we call models. So, the census would also have a component to advance marine ecosystem and other models to use the new data to explain and predict changes in populations and relations among them. A major outcome of the census would be an online three-dimensional geographical information system that would enable researchers or resource managers anywhere to click on a volume of water and bring up data on living marine resources reported in that area. Additionally, the observational system put in place for scientific purposes could serve as the prototype for a continuing diagnostic system for observing living marine resources. A proper worldwide census might cost a total of $1 billion over 10 years. Costly, complicated observational programs prudently begin with pilot projects, to test both techniques and political will.

Not only technology and stressed fisheries but also an international treaty to protect biodiversity make the time ripe for this worthy way. Biodiversity now finds itself with many signatories to its convention, but uncharted national obligations and resources. Acousticians, marine engineers, marine ecologists, taxonomists, statisticians, and others should join their talents to make the Census of Marine Life happen. In fact, some of us, supported by the Alfred P. Sloan Foundation, are trying.[2]

The Great Reversal

Humanity's primitive hunting of the oceans has damaged marine habitats and populations. Fortunately, on the land where humanity stands, engineering and science have infused farming and logging, so initiating the "great reversal." The great reversal refers to human contraction in nature, after millennia of extension, as measured in area, square kilometers or hectares. Simple area is the best single measure of human disturbance of environment.

People transform land by building, logging, and farming (Waggoner et al., 1996). The spread of the built environment includes not only roads, shopping centers, and dwellings, but also lawns, town gardens, and parks. In the United States the covered land per capita ranges from about 2,000 square meters (m^2) in states where travel is fast, like Nebraska, to less than a third as much in slower, more urban New York. The 30 million Californians, who epitomize sprawl, in fact average 628 m^2 of developed land each, about the same as New Yorkers.

The transport system and the number of people in an area basically determine the amount of covered land. Greater wealth enables people to buy higher speed, and when transit quickens, cities spread. Average wealth and numbers will grow, so cities will take more land.

What are the areas of land that may be built upon?

The U.S. population is growing fast, with about another 100 million people expected over the next 75 years, when the world is likely to have about 10 billion. At the California rate of 600 m^2 each, the total U.S. increase would consume 6 million hectares, or about 15 percent of California. Globally, if everyone builds at the present California rate, 4 billion more people would cover about 240 million hectares, or six to seven Californias. By enduring crowding, urbanites spare land for nature. By enduring more crowding, they could spare more. Still, cities will take more land. Can changes in logging and farming offset the urban sprawl?

Declining Wood Use

Forests are cut to clear land for farms and settlements and to obtain fuel, lumber, and pulp (Wernick et al., 1997). In America, from the time of European settlement until 1900 we chopped fervidly and made Paul Bunyan a hero. Since 1900, however, America's forested area has remained level, and since 1950 the volume of wood on American timberland has grown 30 percent. In the same interval, European forests have increased about 25 percent in volume. The intensity of U.S. wood use, defined as the wood product consumed per dollar of gross domestic product, has declined about 2.5 percent annually since 1900. In 1998 an average American consumed half the timber as a counterpart in 1900.

In the United States, the likely continuing fall in intensity of use of forest products should more than counter the effects of growing population and affluence, leading to an average annual decline of perhaps 0.5 percent in the amount of timber harvested for products. A conservative 1.0 percent annual improvement in forest growth would compound the benefits of steady or falling demand and could shrink the area affected by logging by 1.5 percent annually. Compounded, the 1.5 percent would shrink the extent of logging by half in 50 years. If one-half of this amount occurs by not cutting areas that are now cut, the area spared is 50 million hectares, one-third more than the area of California. Changing technologies, tastes, and economics create similar timberland patterns in numerous countries. Since 1990 forests have increased in 44 of 46 temperate countries, excepting the Czech Republic and Azerbaijan.

The rising productivity of well-managed forests should comfortably allow 20 percent or less of today's forest area of about 3 billion hectares to supply world commercial wood demand in the middle of the twenty-first century (Sedjo and Botkin, 1997). Unmanaged forests now yield yearly an average of 1–2 cubic meters (m^3) of commercially valuable species per hectare. The potential yield in secondary temperate forests ranges between 5 and 10 m^3. Many commercial plantation forests now reliably produce more than 20 m^3 per year, and experimental plots have yielded over 60 m^3.

In poor regions of tropical countries such as Brazil, Indonesia, and Congo, the dominant force stressing forests remains the struggle to subsist. During the last two decades, the removal of tropical forests has been estimated at 1 percent per year. Until overcome by better livelihoods, cheap land, cheaper fuels, superior alternatives to wood in the marketplace, or taboos, the one-time conversion of forests to money, cropland, or fuel will continue. Nevertheless, global expansion of forests and rising incomes are encouraging. Indeed, in Latin America alone, about 165 million hectares (or four Californias) once used for crops and pasture have reverted to secondary forest.

Since 1990 forests have increased in 44 of 46 temperate countries.

This brings us to farms. For centuries farmers expanded cropland faster than the population grew, and thus cropland per person rose. Fifty years ago farmers stopped plowing up more nature per capita, initiating the great reversal (Figure 1). Meanwhile, growth in calories in the world's food supply has continued to outpace population, especially in poor countries. Per hectare, farmers have lifted world grain yields about 2 percent annually since 1960.

Frontiers for agricultural improvement remain wide open, as average practice moves steadily toward the present yield ceiling and the ceiling itself keeps rising. On the same area, the average world farmer consistently grows about 20 percent of the corn of the top Iowa farmer, and the average Iowa farmer advances in tandem about 30 years behind the yield of his or her most productive neighbor. While an average Iowa corn farmer now grows 8 tons per hectare, top producers

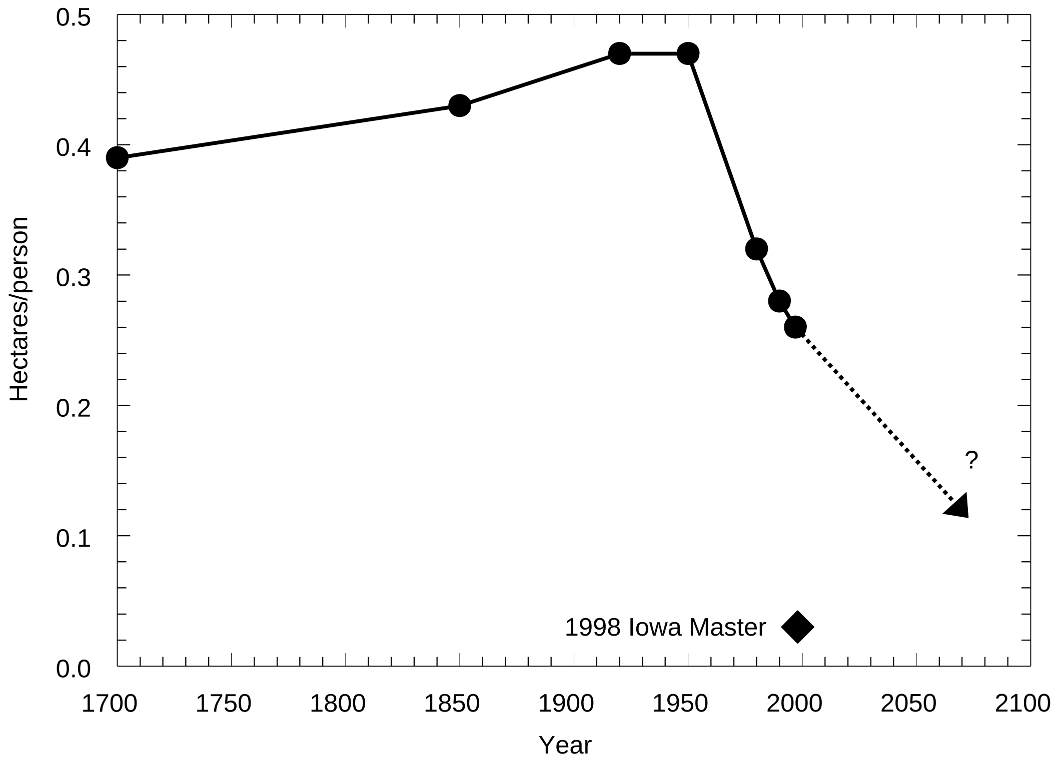

FIGURE 1 The great reversal. After gradually increasing for centuries, the worldwide area of cropland per person began dropping steeply in about 1950, when yields per hectare began to climb. The diamond shows the area needed by the Iowa Master Corn Grower of 1998 to supply one person a year's worth of calories. The dotted line shows how sustaining the lifting of average yields 2 percent per year extends the reversal. SOURCES: U.N. Food and Agriculture Organization Yearbooks; Wallace's Farmer, March 1999; J. F. Richards, 1990.

grow more than 20 tons, and the world average for all crops is about 2 tons. On 1 hectare the most productive farmers now make the calories for a year for 80 people; their grandparents struggled to make the calories for 3.

High and rising yields are today the fruit of precision agriculture. Technology and information help the grower use precise amounts of inputs—fertilizer, pesticides, seed, water—exactly where and when they are needed. Precision agriculture includes grid soil sampling, field mapping, variable rate application, and yield monitoring tied to global positioning. Precision agriculture is frugal with inputs, like other forms of lean production that now lead world manufacturing.

If, during the next 60–70 years, the world farmer reaches the average yield of today's U.S. corn grower (less than 40 percent of today's ceiling), 10 billion people, eating on average as people now do, will need only half of today's cropland. The land spared exceeds the Amazonia. This sparing will happen if farmers maintain the yearly 2 percent worldwide growth of grains achieved since 1960. In other words, if innovation and diffusion continue as usual, feeding people will not stress habitat for nature. Even if the rate of global improvement falls to half, an area the size of India will revert from agriculture to woodland or other uses. A meaty U.S. diet of 6,000 primary calories per day doubles the difficulty or halves the land spared.

In summary, if an additional 4 billion people pave and otherwise develop land at the present rate of Californians, cities will consume about 240 million hectares. This area appears likely to be offset by land spared from logging in the United States and other countries that are now reducing their cutting of forests. The land likely to be spared from crops (over the time it takes to reach 10 billion people) suggests a net worldwide return to nature of lands equal to India, or more than six Californias.

On land as in the oceans, anecdotes, affection for nature, and the plight of poor farmers and loggers will impel nations to spend and prohibit. The goal of my second worthy way, verifying and forecasting the probable extent of the great reversal, is first to guide and then strengthen these actions so they will produce the hoped for conservation and restoration unalloyed by the disillusionment of failure. The distribution of lands spared will greatly affect the chances re-created for flora and fauna.

The research for the great reversal includes observations as well as experiments and analyses. In many parts of the world, routine aerial surveys of land use, confirmed by ground measurements, remain far from complete or usefully periodic. Geographers, foresters, agronomists, ecologists, agricultural and civil engineers, and technologists need to agree on definitions, protocols, and priorities for building the world land information system. The potential of intensively managed forests exemplifies the need for experiment and analysis.

Frameworks for studying the great reversal exist in the large international Global Change Program of environmental research and in joint efforts of the World Bank and World Wildlife Fund for forest conservation. These programs hunger for a feasible, attractive technical vision. Excluding costs for satellites, which I believe have already contributed what answers they can to this question, I estimate that for about $100 million we could verify the great reversal and forecast its probable extent. The information would chart a new sound and grand strategy for conserving the landscape and the other animals with which we share it.

Human Exposure Assessment

My first two ways to spend have been worthy because they would deepen our understanding of sea and land and create the context for protecting other life while we feed ourselves. My third worthy way to spend concerns what we humans absorb from the environment. Recall our high fears and outlays for ionizing radiation, pesticides, and asbestos.

Like other animals, we take in water, food, air, and dust. Given our genes, we are what we eat in the broadest sense, yet little research chronicles actual human exposures. Exposure estimates often trace back to very indirect measures, such as chimney emissions, and our habits and habitats seem overlooked. One wonders why so much exposure measurement and regulation have concentrated on traffic intersections when we spend only one hour each day outside or traveling, and are usually home sleeping (Wiley et al., 1991). Moreover, exposures to even a single chemical may occur from contact with several media (air, water), via several pathways (hand-to-mouth transfers, food), and through several routes (inhalation, oral, dermal).

In 1994, to gather information about the magnitude, extent, and causes of human exposures to specific pollutants and measure the total "dose" of selected pollutants that Americans receive, the Environmental Protection Agency (EPA) launched a National Human Exposure Assessment Survey (NHEXAS) (*Journal of Exposure Analysis and Environmental Epidemiology,* 1995). Its ultimate goal is documenting the status and trends of national exposure to risky chemicals both to improve risk assessments and to evaluate whether risk management helps.

Little research chronicles actual human exposures.

For pilot studies, EPA chose metals, volatile organic compounds, pesticides, and polynuclear aromatics, because of their toxicity, prevalence in the environment, and relative risk to humans—at least as perceived by EPA and perhaps the general public. I never forget Bruce Ames's work showing that 99.99 percent of the pesticides we ingest are natural (Ames et al., 1990). In any case, EPA's chosen classes of compounds and the expected combination of chemicals, exposure media, and routes of exposure would demonstrate and challenge currently available analytical techniques.

Phase I of this effort, including demonstration and scoping projects, may already be the most ambitious study of total human exposure to multiple chemicals on a community and regional scale. It has focused on exposure of people to environmental pollutants during their daily lives. Several hundred survey participants wore "personal exposure monitors" to sample their microenvironments, and NHEXAS researchers measured levels of chemicals to which participants were exposed in their air, foods, water and other beverages, and in the soil and dust around their homes. They also measured chemicals or their metabolites in blood and urine provided by participants. Finally, participants completed time-activity questionnaires and food diaries to help identify sources of exposure to chemicals and to characterize major activity patterns and conditions of the home environment. Sample collection began in 1995 and went to early 1998. Publications and databases are expected soon.

The main purpose of the pilot study is to find the best way to conduct the full national human exposure assessment survey. Implementing representative monitoring projects to estimate the magnitude, duration, frequency, and the spatial and temporal distribution of human exposures for the United States will be a large task, involving chemists, biologists, statisticians, and survey researchers. I hope clever engineers can lighten, integrate, and automate the measurement processes, and speed the reporting efforts.

I learned of NHEXAS while serving for three years on the executive committee of EPA's Science Advisory Board. NHEXAS was an unpolished diamond in a lackluster research portfolio. Neither EPA's leadership nor the Congress appreciated the survey, so it has proceeded slowly and barely. I estimate the cost to perform NHEXAS right might be $200 million over six to seven years. I believe the United States should make a strong commitment to it, though not exactly as underway. It needs a less "toxic" bias. A national scientific conference to adjust and advance the concept might be timely.

We may find surprisingly powerful levers to reduce ambient bads or increase goods.

The eventual outcomes of NHEXAS should include a comprehensive total human exposure database and models that accurately estimate and predict human exposures to environmental chemicals for both single and multiple pathways. The models would link environmental and biological data with information on human activity to estimate total human exposures to various chemicals and combinations, and thus contribute to better risk assessments. We can establish proper baselines of normal ranges of exposure and identify groups likely to be more exposed.

We know surprisingly little about our exposures. For decades researchers have measured and tracked pollutants one at a time, often faddishly. This third worthy way can reduce the uncertainty about exposure and indeed make exposure a science. Understanding aggregate exposures, we may find surprisingly powerful levers to reduce ambient bads or increase goods.

Zero-Emission Power Plants

One way to finesse the question of exposure, whether for humans or green nature, is with industries that generate zero emissions. A growing group of engineers has been promoting the concept of industrial ecology, in which waste tends toward zero, either because materials that would become waste never enter the system, or because one manufacturer's wastes become food for another in a nutritious industrial food chain, or because the wastes are harmless. I, for one, certainly want zero emissions of poisonous elements such as lead and cadmium.

For green nature exposed outdoors, however, the major emission is carbon, and reducing this emission to zero is the purpose of my fourth worthy way. Today, industries annually emit about 6 gigatons of carbon to the atmosphere, or a ton per each of the planet's 6 billion people. The mounting worry is that these and more gigatons likely to be emitted will make a punishing climate for nature exposed outdoors.

Most of the carbon comes, of course, from fuel to energize our economies, and an increasing portion of the energy is in the form of electricity. Since Thomas Edison, the primary energy converted to electricity has grown in two sequential, long S curves until it is now about 40 percent of all energy humanity uses. Although electric consumption leveled until recently at the top of its second S curve, I believe it will maintain an average 2–3 percent annual growth through the twenty-first century. In the information era, consumers will surely convert even more of their primary energy to electricity. And, after all, 2 billion people still have no electricity. In 2100, after a hundred years of 2–3 percent growth per year, the average per capita electricity consumption of the world's 10 billion people or so would be raised only to today's average U.S. per capita consumption.

To eliminate carbon emissions, I must first ask what fuel is used to generate electricity. As shares of primary energy sources have evolved from wood and hay to coal, to oil, and then to natural gas, with more hydrogen per carbon atom, the energy system has gradually and desirably been decarbonized (Ausubel, 1991). Nuclear fuel, probably, or possibly some other noncarbon alternative, will eventually close the hydrocarbon fuel era. In the interim, however, can we find technology consistent with the evolution of the energy system to economically and conveniently dispose of the carbon produced from making kilowatts? My fourth worthy way—zero-emission power plants (ZEPPs)—offers just that: a practical means to dispose of the carbon from generating electricity consistent with the future context.

Natural Gas First

The first step on the road to ZEPPs is to focus on natural gas, simply because it will be the dominant fuel, providing perhaps 70 percent of primary energy around the year 2030 (Ausubel et al., 1988). Although natural gas is far leaner in carbon than other fossil fuels, in 2030 it can be expected to contribute about 75 percent of total CO_2 emissions.

One criterion for ZEPPs is that they must work on a big scale. In 2060, the expected peak use of 30×10^{12} m^3 of natural gas would produce two to three times today's carbon emissions. Even in 2020, we could already need to dispose of carbon from natural gas alone equal to half of today's emissions from all fuels.

Big total use means big individual ZEPPs because the size of generating plants grows even faster than use. In concert with the overall electric system, the maximum size of power plants has grown in S-shaped pulses. One pulse, centered in the 1920s, expanded power plants from a few tens of megawatts (MW) to more than 300. After a stagnant period, another pulse centered near 1970 quadrupled the maximum plant size to about 1,400 MW. Now the world nears the end of another period of stagnation in maximum size. Engineers must prepare for increased electricity use during the next 50 years to lift the peak plant size to 5,000 MW or 5 gigawatts (GW). For reference, the New York metropolitan area now draws above 12 GW on a peak summer day.

Plants grow because large scale means lower cost, assuming the technology can cope. Crucial for controlling emissions, one big plant emits no more than many small plants but emission from one is easier to collect. We cannot solve the carbon question if we need to collect emissions from millions of microturbines.

So far, I've specified this worthy way as a search for big ZEPPs fueled by natural gas. But bigger ZEPPs mean transmitting immense power from larger and larger generators through a large steel axis at a speed such as 3,000 revolutions per minute (RPM). One way around the limits of mechanical power transmission may be shrinking the machinery. Begin with a very high pressure CO_2 gas turbine where fuel burns with oxygen. Pressure ranging from 40 to 1,000 atmospheres would enable the CO_2 to recirculate as a liquid, and the liquid combustion products could then be bled out.

Very high pressures shrink the machinery.

Fortunately for transmitting power, the very high pressures shrink the machinery in a revolutionary way and permit very fast RPMs for the turbine. The generator could then also turn very fast, operating at high frequency, with appropriate power electronics to slow the output to 50 or 60 cycles. People have seen the attraction of higher RPMs for a while, and high-RPM generators were included in the last version of a gas turbine of the high-temperature reactor designed by General Atomics Corporation.

Materials issues lurk and solutions are expensive to test. Problems of stress corrosion and cracking will arise. The envisioned temperature of 1500°C has challenged aviation engineers for some time. Fortunately, engineers have recently reported a tough, thermally conductive ceramic strong up to 1600°C in air (Ishikawa et al., 1998).

Although combustion within CO_2 does not appear to be a general problem, some difficulties may arise at the high temperatures and pressures. Also, no one has yet made burners for pressures as high as we consider. Power electronics to slow the cycles of the alternating current raise big questions, and so far, the costs of such power electronics exceed the benefits. The largest systems for conversion between alternating and direct current are now 1.5 GW and can handle 50–60 cycles. What we envision is beyond the state of the art, but power electronics is still young, meaning expensive and unreliable, and we are thinking of the year 2020 and beyond when this worthy way could make it mature, cheap, and reliable. Already engineers consider post-silicon power electronics with diamond plasma switches.

Providing the requisite oxygen for a ZEPP, say, 1,000 tons per hour for a 5-GW plant, also exceeds present capacity (about 250 tons of oxygen per hour, produced by cryoseparation), but it could be done. Moreover, a cryogenic plant may introduce a further benefit. The power equipment suppliers tend to think of very large and slow-rotating machines for high unit power, which cause problems due to the mechanical resistance of materials. With a cryogenic plant nearby, we might recur to superconductors that work in the cool context.

ZEPPs could be the workhorses of the energy system.

With a ZEPP fueled by natural gas transmitting immense power at 60 cycles, the next step is to sequester the waste carbon. Because of the high pressure, the waste carbon is, of course, already easily handled liquid CO_2. In principle, aquifers can store CO_2 forever if their primary rocks are silicates, which with CO_2 become stable carbonates and silica (SiO_2). The process is the same as rocks weathering in air. The Dutch and Norwegians have done a lot of research on CO_2 injection in aquifers, and the Norwegians have already started injecting.

Opportunities for storing CO_2 will join access to customers and fuel as key factors in determining plant locations. Fortunately, access to fuel may become less restrictive. Most natural gas travels far through a few large pipelines, which makes these pipelines the logical sites for generators. The expanding demand will require a larger and wider network of pipelines, opening more sites for ZEPPs.

Another criterion is overall projected plant efficiency, now reaching about 50 percent. Colleagues at Tokyo Electric Power calculate that the efficiency of the envisioned ZEPP could be 70 percent.

In short, the fourth worthy way is a supercompact (1–2 m in diameter), superpowerful (potentially 10 GW, or double the expected maximum demand), superfast (30,000 RPM) turbine putting out electricity at 60 cycles, plus CO_2 that can be sequestered. ZEPPs the size of a locomotive or eventually an automobile, attached to gas pipelines, might replace the fleet of carbon-emitting nonnuclear monsters now cluttering our landscape.

We propose starting introduction of ZEPPs in 2020, leading to a fleet of 500 5-GW ZEPPs by 2050. This does not seem an impossible feat for a world that built today's worldwide fleet of some 430 nuclear power plants in about 30 years. Combined with the oceans safely absorbing 2–3 gigatons of carbon yearly, ZEPPs, together with another generation of nuclear power plants in various configurations, can stop CO_2 increase in the atmosphere near 2050, well below the doubling of atmospheric CO_2 about which people worry, without sacrificing energy consumption.

Research on ZEPPs could occupy legions of academic researchers and provide new purpose to the Department of Energy's laboratories, working on development in conjunction with private-sector companies. The fourth worthy way to spend merits tens of billions in R&D because the ZEPPs will form a profitable industry worth much more to those who can capture the expertise to design, build, and operate them. Like all my worthy ways, ZEPPs need champions.

To summarize, we have searched for technologies that handle the separation and sequestration of amounts of carbon matching future fuel use. Like the 747 jumbo jets that carry about 80 percent of passenger kilometers, compact and ultrapowerful ZEPPs could be the workhorses of the energy system in the middle of the next century.

Maglevs

Cutting emissions and the footprints of farming, logging, and power, we naturally also wonder about transport. Transport now covers Earth with asphalt ribbons and roars through the air leaving contrails that could prove harmful. With cars shifting to fuel cells fed with hydrogen over the next few decades, the air transport system and its jet fuel can become emissive enemy number one. Fortunately, the time is right for innovation in mobility, my fifth worthy way.

Since 1880, U.S. per capita mobility, including walking, has increased 2.7 percent per year, and the French about the same. Europeans currently travel at about

35 kilometers per hour and per day, because people travel about 1 hour per day. Of this, Europeans fly only about 20 seconds or 3 kilometers per day. A continuing rise in mobility of 2.7 percent per year means a doubling in 25 years, or an additional 35 kilometers per day, about 3 minutes on a plane. Three minutes per day equal about one round-trip per month per passenger. Americans already fly 70 seconds daily, so 3 minutes certainly seems plausible for the average European a generation from now. The jetset in business and society already flies a yearly average of 30 minutes per day. However, for the European air system, the projected rise in mobility would require a 14-fold increase in 25 years, or about 12 percent per year. The United States would need a 20-fold increase in 50 years. A single route that carries one million passengers per year per direction would require dozens of takeoffs and landings of jumbo jets daily. At a busy airport the jumbos would need to take off like flocks of birds. This is unlikely. We need a basic rethinking of planes and airport logistics.

The history of transport can be seen as a striving to bring extra speed in response to the progressively expanding level of income and the fixed amount of time we are willing to expose ourselves to travel (Ausubel et al., 1998). According to a rhythmic historical pattern (Figure 2), a new, fast transport mode should enter about 2000. The steam locomotive went commercial in 1824, the gasoline engine in 1886, and the jet in 1941. In 1991, the German Railway Central Office gave the magnetic levitation (maglev) system a certificate of operational readiness and a Hamburg-Berlin line is now under construction. The essence of the maglev is that

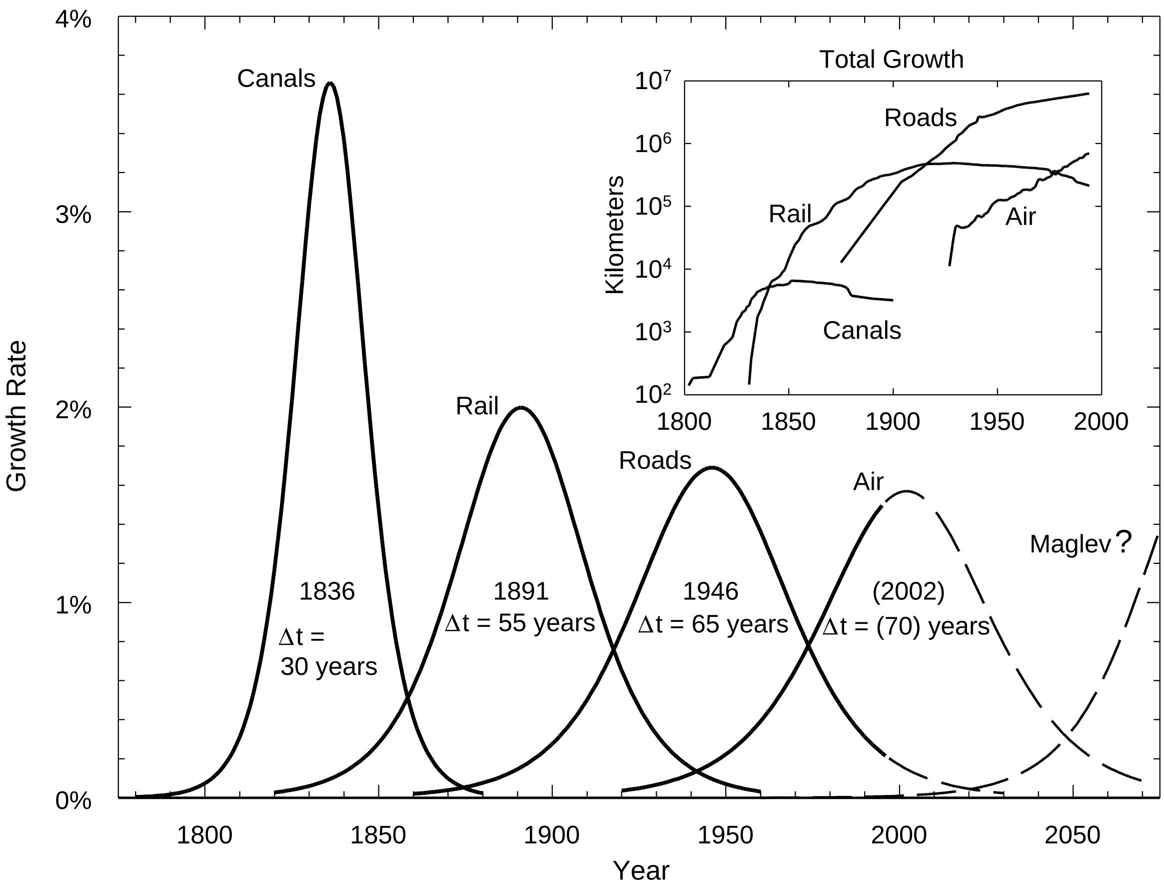

FIGURE 2 U.S. transport growth. The solid lines show smoothed historic rates of growth of the major components of the U.S. transport infrastructure. The dashed lines show conjectures based on constant dynamics. The years are the midpoints of the processes, and delta t is the time for the system to grow from 10 to 90 percent of its extent. The inset shows the actual growth, which eventually became negative for canals and rail as routes were closed. SOURCE: J. H. Ausubel, C. Marchetti, and P. S. Meyer, 1998.

magnets lift the vehicle off the track, thus eliminating friction, and that activation of a linear sequence of magnets propels the vehicle.

Maglevs have many advantages: not only high mean speed, but acceleration, precision of control, and absence of noise and vibration. They can be fully passive to forces generated by electrical equipment and need no engine on board. Maglevs also provide the great opportunity for electricity to penetrate transport, the end-use sector from which it has been most successfully excluded.

The induction motors that propel maglevs can produce speeds in excess of 800 kilometers per hour, and in low-pressure tunnels speeds can reach thousands of kilometers per hour. In fact, electromagnetic linear motors allow constant acceleration. Constant acceleration maglevs (CAMs) could accelerate for the first half of the ride and brake for the second, thus offering a very smooth ride with high accelerations.

The vision is small vehicles, rushing from point to point.

High speed does entrain problems: aerodynamic and acoustic as well as energetic. In tunnels, high speed requires large cross sections. The neat solution is partially evacuated tubes, which must be straight to accommodate high speeds. Low pressure means a partial vacuum comparable to an altitude of 15,000 meters. Reduced air pressure helps because above about 100 kilometers per hour the main energy expense to propel a vehicle is air resistance. Low pressure directly reduces resistance and opens the door to high speed with limited energy consumption. Tunnels also solve the problem of landscape disturbance.

For a subsurface network of such maglevs, the cost of tunneling will dominate. The Swiss are actually considering a 700-kilometer system. For normal high-speed tunnels, the cross-section ratio of tunnel to train is about 10 to 1 to handle the shock wave. With a vacuum, however, even CAMs could operate in small tunnels, fitting the size of the train. In either case the high fixed cost of infrastructures will require the system to run where traffic is intense or huge currents can be created, that is, in trunk lines. Because the vehicles will be quite small, they would run very often. In principle, they could fly almost head to tail, 10 seconds apart.

Initially, maglevs will likely serve groups of airports, a few hundred passengers at a time, every few minutes. They might become profitable at present air tariffs at 50,000 passengers per day. In essence, maglevs will be the choice for future metros at several scales: urban, possibly suburban, intercity, and continental. The vision is small vehicles, rushing from point to point. Think of the smart optimizing elevators in new skyscrapers. With maglevs, the issue is not the distance between stations, but the waiting time and mode changes, which must be minimized. Stations need to be numerous and trips personalized, with zero stops or perhaps one.

Technical Considerations

Technically, among several competing designs the side-wall suspension system with null-flux centering seems especially attractive: simple, easy access for repair, and compact (U.S. Department of Transportation, 1993). Critically, it allows vertical displacement and therefore switches with no moving parts. Vertical displacement can be precious for stations, where trains would pop up and line up without pushing other trains around. It also permits a single network, with trains crossing above or below. Alternatively, a hub-and-spoke system might work. This design favors straight tubes and one change.

The suspension system evokes a comparison with air. Magnetic forces achieve low-cost hovering. Planes propel by pushing air back. Momentum corresponds to the speed of the air pushed back, that is, the energy lost. Maglevs do not push air back, but in a sense push Earth, a large mass, which can provide momentum at negligible energy cost. The use of magnetic forces for both suspension and propulsion appears to create great potential for low travel-energy cost, conceptually reduced by one to two orders of magnitude with respect to energy consumption by airplanes with similar performance.

Because maglevs carry neither engines nor fuel, the weight of the vehicle can be light and the total payload mass high. Airplanes at takeoff, cars, and trains all now weigh about 1 ton per passenger transported. A horse is not much lighter. Thus, the cost of transport has mainly owed to the vehicle itself. Maglevs might weigh 200 kilograms per passenger.

At intercity and continental scale, maglevs could provide supersonic speeds where supersonic planes cannot fly. For example, a maglev could fuse all of mountainous Switzerland into one functional city in ways that planes never could, with 10-minute travel times between major present city pairs.

Traveling in a CAM for 20 minutes, enjoying the gravitational pull of a sports car, a woman in Miami could go to work in Boston and return to cook dinner for her children in the evening. Bostonians could symmetrically savor Florida, daily. With appropriate interfaces, the new trains could carry hundreds of thousands of people per day, saving cultural roots without impeding work and business in the most suitable places.

Seismic activity could be a catch. In areas of high seismic activity, such as California, safe tubes (like highways) might not be a simple matter to design and operate.

Although other catches surely will appear, maglevs should displace the competition. Intrinsically, in the CAM format they have higher speed and lower energy costs and could accommodate density much greater than air. They could open new passenger flows on a grand scale during the twenty-first century with zero emissions and minimal surface structures.

We need to prepare a transport system that can handle huge fluxes of traffic. Growth of 2.7 percent per year in passenger kilometers traveled means not only the doubling of mobility in 25 years but a 16-fold increase in a century, which is the rational time for conceiving a transport system. The infrastructures last for centuries. They take 50–100 years to build, in part because they also require complementary infrastructures. Moreover, the new systems take 100 years to penetrate fully at the level of the consumer. Railroads began in the 1820s and peaked with consumers in the 1920s.

It is time for my fifth worthy way, to conceive in detail maglevs for America and to develop the required skills, such as tunneling. Universities should be producing the needed engineers, operations researchers, and physicists, and government should partner with industry on the prototypes. Like ZEPPs, maglevs will bring huge revenues to those who can design, build, and operate them, anywhere in the world.

Closing Remarks

A worldwide census of marine life can reawaken the adventure of the age of discovery and teach us how to spare marine habitats. A study of the great reversal of human extension into the landscape can inspire us to lift yields and spare land for nature. NHEXAS can show what we absorb and how to spare exposures. ZEPPs can generate many gigawatts without harmful emissions, sparing the climate. And maglevs can multiply our mobility while sparing air and land. These worthy ways to spend on environment and resources cohere in the vision of a large prosperous human economy that treads lightly and emits little or nothing.

Maglevs can multiply our mobility while sparing air and land.

Research is a vision or dream in which we, like Leonardo da Vinci, simulate a machine first in our mind. Leonardo's powers of visualization, or one might say of *experiment*, were so great that his machines work, even if the letting of contracts and construction is delayed 500 years. Building machines is often costly. Dreaming is cheap. Let us start now with these five worthy ways to spend that can make dreams of improving the human condition and environment so irresistibly beautiful and true that societies, especially America, hasten to let the contracts and build the machines that can spare planet Earth—soon instead of after a delay of 500 years.

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Notes

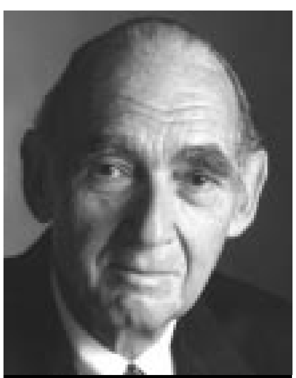
1 Thanks to Edward Frieman and William Nierenberg for hosting my visit to the San Diego Science & Technology Council, La Jolla, Calif., 9 December 1998. Thanks also to Cesare Marchetti, Perrin Meyer, and Paul Waggoner for helping develop these worthy ways over many years.

2 The Consortium for Oceanographic Research and Education in Washington, D.C., has now established an international steering committee to develop a plan for the census. More information can be found online at http://core.cast.msstate.edu/censhome.html.

Alternative Pathways to a Carbon-Emission-Free Energy System

Henry R. Linden

There has developed a broad consensus that energy systems will move towards electricity for all stationary energy uses, and to hydrogen (compressed, adsorbed, or liquefied) for transportation fuel.



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Over the past several decades there have been drastic changes in the perception of the forces driving the evolution of the global energy system. Technological advances and increased efficiency have calmed fears of large price increases and early exhaustion of the most desirable fossil fuels—oil and natural gas. In fact, during 1998, oil prices in deflated terms dropped to a 50-year low. Natural gas, although not nearly as fungible as oil, has become a widely traded commodity because of the growing importance of liquefied natural gas and the use of transnational pipelines to provide clean and competitively priced energy in areas without indigenous gas resources. In the United States, composite spot wellhead prices of natural gas have generally remained below \$2/million Btu (\$11.60/barrel crude oil equivalent) since 1987, and are expected to rise to only \$2.61/million Btu in constant 1997 dollars by 2020 (Energy Information Administration, 1998). The prophets of doom, who predict early peaking of global crude oil and natural gas capacity on the basis of outdated theories, will again prove to be wrong, as they often have in the past (Laherrere, 1999; Linden, 1998). Coal, because of its much greater abundance than oil and natural gas, is not subject to fears of long-term supply problems. However, in a world increasingly concerned with environmental quality, coal is under growing market pressure, and this has further driven down its current and projected costs relative to other primary energy sources.

It has long been expected that the global energy system will continue to evolve in historical cycles, as it has from a primary reliance on wood, then on coal, and now on oil, to some time during the twenty-first century on natural gas, followed by a yet uncertain mix of renewable energy sources and nuclear power. The growing global abundance of natural gas, its desirable environmental qualities, and the relative ease and efficiency of its conversion to electricity have made it the logical transition fuel to a sustainable energy system, and bode well for its capturing the largest share of the primary energy market during the next 50 years or so. However, in recent years, a new consideration has become dominant in shaping the future of the global energy mix. It is the realization that it is probably unwise to liberate a major share of the roughly 5,000 billion metric tons (gigatonnes) of carbon in the technically recoverable fossil fuels in the form of carbon dioxide (CO_2) because of the potential impact on climate. Thus, there is now a great impetus to move as quickly as possible to a global energy system that is free of carbon emissions.

PEM electrolyzers produce chemically pure hydrogen.

As noted before, it has been anticipated that technological advances would make fossil fuels obsolete by the end of the twenty-first century, just as coal made fuel wood in the middle of the nineteenth century. In fact, even during the late 1960s and early 1970s, the Institute of Gas Technology developed the concept of a "hydrogen economy" in which nonfossil sources of hydrogen would eventually replace natural gas (Linden, 1971). Now, hydrogen is again considered to be the key to a sustainable energy future. The major U.S. automobile manufacturers have already made a commitment to its use in propulsion systems with triple the efficiency of conventional internal-combustion engines.

Over the longer term, hydrogen is considered the ideal energy storage medium for intermittent renewable energy sources such as photovoltaic and wind power, and could possibly be an alternative to electricity as an energy carrier. However, earlier enthusiasm for hydrogen as a direct source for stationary energy applications has now diminished because of its high cost of transmission and distribution, and potential technical and safety problems in its utilization as a substitute for natural gas. Instead, there has developed a broad consensus that energy systems will move towards electricity for all stationary energy uses, and to hydrogen (compressed, adsorbed, or liquefied) for transportation fuel. In recent years, the debate over the likely endpoint of this evolution has been mostly about the relative roles of nuclear power and the various renewable sources of power (solar, wind, hydropower, biomass, etc.). Also, among the renewables, there has been debate over the relative roles of biomass and energy crops in general, with specific concerns about excessive land requirements and environmental impacts.

A Change in Thinking

Now, another drastic change in thinking has occurred among some of today's most prominent advocates of the hydrogen economy. The new thinking accepts the use of electricity and hydrogen but plans to obtain the hydrogen from fossil fuel reforming or gasification and then separate and sequester the CO_2 formed in these processes (Hileman, 1997). In these well-known processes, fossil fuels are converted with oxygen and/or steam into mixtures of hydrogen, carbon monoxide (CO) and CO_2, and the CO is then further converted with steam into more hydrogen and CO_2. In carbon sequestration, the resulting CO_2 is captured and stored in geological formations or the deep ocean. These techniques raise many new issues regarding the most cost-effective and socially least disruptive pathway to sustainability. For example, what should determine the relative amounts of research, development, and demonstration (RD&D) investments in the various renewable power sources, in the emerging resources of natural gas, and in fossil fuel reforming/gasification with carbon sequestration?

As noted before, the die is already cast in respect to surface transport shifting to more efficient electromotive propulsion. It appears that most vehicles will eventually be powered with hydrogen stored on board and converted to electricity with air in proton exchange membrane (PEM) fuel cells, used in tandem with advanced batteries for startup, peak power, and the capture of braking energy. Only inadequate global supplies of platinum, used as a catalyst in PEM fuel cells, are likely to constrain this option (Appleby, 1999). Hydrogen produced on board by reforming of gasoline or methanol is unlikely to prove practical because of operational and economic disadvantages (Thomas, 1998). This option was always based on a misperception of the cost of creating a hydrogen refueling infrastructure. Hydrogen "filling stations" do not depend on a transmission and distribution network similar to that for natural gas, but can be dispersed systems, initially using natural gas steam reformers for hydrogen production, but soon using PEM water electrolyzers to split water into hydrogen and oxygen. Eventually, electrolyzers will be powered with solar (photovoltaic) energy, but in the interim could be powered by cheap off-peak power.

PEM electrolyzers produce chemically pure hydrogen, thereby avoiding fuel cell anode poisoning problems. They also reduce compression costs because they are capable of delivering hydrogen at pressures as high as 2,000 pounds per square inch. Admittedly, in areas where most of the off-peak power is generated from coal or other fossil fuels in steam-electric plants, the power required to produce hydrogen for surface transportation fuel would increase greenhouse gas emissions compared to other propulsion options (Thomas, 1997). However, hydrogen produced by natural gas reforming does not have this disadvantage. In any event, this will be a temporary problem. Over the next 20–30 years, highly efficient combined-cycle turbine systems, fired by natural gas, will replace current fossil fuel systems. They emit only one-third as much CO_2, and cost only one-third as much, as today's coal-fired steam-electric plants. Also, by then, photovoltaic power modules integrated with PEM electrolyzers or reversible PEM fuel cells/electrolyzers might be competitive for both hydrogen production and energy storage.

Issues Raised by the Carbon Sequestration Option for Continued Reliance on Fossil Fuels

Clearly, the abundance of fossil fuels, especially coal, in combination with cost-effective processes for gasification and carbon sequestration, offers an alternative to using natural gas as a transition fuel on the path to zero-carbon-emission technologies. In the most vigorously advocated embodiment of the carbon sequestration option, hydrogen from large coal-gasification plants would be used to generate power on-site and as a regional transportation fuel (Williams, 1999b). This raises the following questions:

- In the absence of proof of technical feasibility, how reliable are the projected economics of hydrogen production from coal and carbon sequestration using such new technologies as ceramic membranes for hydrogen separation (Williams, 1999b)?

Hydrogen is considered to be the key to a sustainable energy future.

- Who will make the huge investments in coal-based hydrogen production, carbon sequestration, centralized hydrogen power generation facilities, and the associated electric and hydrogen transmission systems? It seems unlikely that it will be the restructured utilities in the United States, which are rapidly becoming "wires only" businesses. If private investors cannot be enticed to take the risk of competing with currently cheaper sources of power and hydrogen, is this a prescription for massive public power projects?
- Are there not major environmental impacts, including the release of greenhouse gases such as methane, caused by mining and transporting coal, as well as unavoidable health and safety problems?
- Is it really preferable to use hydrogen near its point of production to generate electricity? Or would it be better to use a hydrogen distribution and transmission infrastructure equivalent to that which now exists for natural gas?
- In the absence of such an infrastructure, how would the hydrogen produced in central coal-gasification facilities be made widely available for surface and air transport? Might it be practical to distribute hydrogen in compressed or liquefied form via trucks or railroad tank cars?

- Would it be advantageous to develop a relatively costly infrastructure for delivering hydrogen to refueling stations, especially since such a system could also serve distributed power generation needs? Should there be a renewed effort to explore the feasibility of gradually converting the existing natural gas infrastructure to hydrogen?
- As an alternative, would the best solution be to have only a power transmission and distribution infrastructure, accept the costs and energy losses of electrolysis, and make the hydrogen for surface and air transport needs in dispersed installations from centrally generated electricity?
- Will it really be feasible to sequester carbon from coal gasification in relatively nearby depleted oil and gas reservoirs, deep coal seams, or aquifers, or will, in many instances, more costly long-distance pipeline transport of CO_2 to sequestering sites have to be considered?
- And, most fundamental of all, are there convincing economic, environmental, political, and institutional arguments to pursue this technologically risky alternative? And if so, can these arguments justify slowing or even halting rapid progress towards an inherently zero-carbon-emission, renewable, or essentially inexhaustible energy system, and also downgrading the valuable role of natural gas as a transition fuel?

Direct conversion of the natural gas transmission grid to pure hydrogen is not feasible.

Earlier studies of hydrogen versus natural gas transmission have indicated that the cost for hydrogen would range from 60 percent higher to as much as 2 to 3 times as much per unit of delivered energy, based on the higher heating value (HHV), but that there may be a slight cost advantage of hydrogen versus high-voltage power transmission (Gregory et al., 1972; Rosenberg and Gregory, 1972). Unfortunately, direct conversion of the existing high-pressure natural gas transmission grid to pure hydrogen is not feasible because of hydrogen embrittlement problems and because of hydrogen's much larger compression power requirements. However, solutions to the embrittlement problem may be found, such as the addition of a small percentage of oxygen (100 parts per million to 1 percent by volume) (Williams, 1996).

A Novel Approach to a Cost-Effective, Coal-Based, Carbon-Emission-Free Energy System

Robert H. Williams of Princeton University has made a strong case for the option of central coal gasification with carbon sequestration. He claims that by 2020 hydrogen could be produced at roughly the same cost per unit of HHV as that projected for natural gas delivered to power plants (Williams, 1999b). This would be achieved through the use of still unproved ceramic membrane devices for hydrogen separation and associated increases in process efficiency. Coal would first be gasified at high pressure and temperature with oxygen from an air separation plant to produce primarily CO. Steam would then be added to convert the CO to CO_2 and hydrogen at a relatively high temperature compared to the conventional catalytic process for performing this water gas shift reaction ($CO + H_2O \rightarrow H_2 + CO_2$). The novel hydrogen separation device would allow progress of the water gas shift reaction to near completion in the absence of a catalyst at this relatively high temperature because the hydrogen, as it is produced, is removed continuously by diffusion through the tubular ceramic membranes. As projected by Williams, the use of the hot, high-pressure waste gas from the ceramic membrane device would produce about twice as much power than on-site requirements. Credits for this export power, in combination with other novel features, would reduce hydrogen production costs to roughly one-half those of conventional coal gasification, water gas shift, and CO_2 removal processes.

In coal-gasification plants based on this scheme and large enough to fuel two 400-megawatt (MW) GE Frame 7-H combined-cycle gas-turbine/steam-turbine plants, Williams claims that without carbon sequestration, hydrogen could be produced in 2020 at about \$3/million Btu (HHV and 1997 dollars). With carbon sequestration in onshore and offshore disposal sites 250–500 kilometers from the plant, the cost would be \$4 to \$4.25/million Btu. This is based on a projected cost of coal delivered to power plants in 2020 of \$0.93/million Btu, again in 1997 dollars (Energy Information Administration, 1998).

Williams estimates that power costs for this essentially carbon-emission-free method of generation will be \$0.043 to \$0.048 per kilowatt-hour (kWh), depending on the type of combined-cycle turbine system employed (i.e., GE Frame 7-F or 7-H). However, this is a substantial premium over power produced with natural gas in combined-cycle turbine units at the projected cost of natural gas delivered to power plants in 2020 of \$3.24/million Btu in 1997 dollars (Energy Information Administration, 1998). Williams calculates this power cost to be \$0.031 to \$0.034/kWh even though the fuel costs 3.5 times as much as coal. He does not really justify the premium of \$0.012 to \$0.014/kWh because he makes his case primarily by pointing to the large value of reducing pollutants and CO_2 emissions via the use of coal-derived hydrogen instead of various coal-fired power generation technologies, including so-called "clean coal" technologies.

Comparing Costs

For example, even compared to the most advanced commercial coal-fired power generation technology—integrated coal-gasification combined-cycle (IGCC) plants—with their relatively high efficiency and low emissions of particulate matter, pollutants, and CO_2, the higher costs of power generated with coal-based hydrogen can apparently be justified by the health benefits. Moreover, the cost of avoiding CO_2 emissions is only \$44/metric ton of carbon (tC), which is within the CO_2 disposal cost range of \$35 to \$45/tC cited by Williams (1999b). But this reasoning does not apply to comparisons with modern natural gas technologies. For example, using Williams's data, natural-gas-fueled combined-cycle plants emit only 37–49 percent as much CO_2 as modern clean coal-fired power generation plants. Natural-gas-fired combined-cycle plants also have negligible emissions of particulates and other conventional pollutants. In this context, one may question Williams's comparison of power costs of \$0.036 to \$0.037/kWh with coal-based hydrogen in which the CO_2 is vented, with natural-gas-fueled power costs of \$0.031 to \$0.034/kWh, because it fails to account for the much higher CO_2 emissions.

In his latest study, Williams acknowledges that many technological and institutional uncertainties face his approach. Most important are the unanswered questions about the ceramic membrane hydrogen separation device itself—such as mechanical stability at the high pressure drop across the membrane; the possible need for catalysis to achieve adequate conversion of CO to hydrogen in a feed gas that contains high concentrations of hydrogen sulfide which poisons conventional water gas shift catalysts; and possible fouling of the membrane with particles that escape an unproved ceramic filter proposed for cleaning the hot synthesis gas that leaves the oxygen-blown coal gasifier. In terms of institutional problems, the greatest is the ability and willingness of the large and rapidly increasing coal users in the developing world, such as China and India, to adopt this radical new technology in view of their limited financial resources. In addition, there are many unanswered geological and environmental questions about the various options for carbon sequestration. Nevertheless, the proposed pathway to zero carbon emissions proposed by Williams merits serious consideration and substantial RD&D investments.

There are many unanswered questions about the options for carbon sequestration.

Coal-Based Hydrogen for Transportation

In contrast with an earlier study by Williams made available as a private communication (Williams, 1999a), Williams's latest study does not elaborate on the means and costs of distributing hydrogen production in excess of that required for central power generation as a transportation fuel. He merely states that 12 percent of excess hydrogen production by each coal-gasification plant that fuels 800 MW of combined-cycle capacity at an 80 percent load factor would support 340,000 fuel cell vehicles traveling 18,000 kilometers per year at a fuel efficiency equivalent to 106 miles per gallon of gasoline. Williams also notes that, if in 1996 all U.S. coal-fired power plants had been converted to combined-cycle plants fueled with coal-based hydrogen and the carbon sequestered, and the 12 percent extra hydrogen produced had been used for fuel-cell-powered transport, one-half of the U.S. light-duty vehicle fleet could have been supported. Together, this would have reduced U.S. CO_2 emissions by 40 percent and oil use by 20 percent, and would have increased U.S. coal use by 7.5 percent.

The ultimate goal would be to have all surface transport powered by hydrogen stored on board.

Presumably, as in the earlier study, the extra hydrogen would be made available to end users through regional transmission grids and refueling stations at a retail cost of about $13/million Btu (HHV and 1997 dollars). At the much higher efficiency of fuel cell vehicles, this would still be competitive with gasoline. In checking this thought experiment against the 305 gigawatts of 1996 U.S. coal-fired capacity, it would yield an excessive number of 130 million vehicles without correcting for the actual 65 percent load factor for U.S. coal-fired generation capacity in 1996, versus the 80 percent assumed by Williams for the hydrogen-fueled combined-cycle plants.

An Alternative Proposal for a Least-Cost Pathway to a Sustainable U.S. and Global Energy System

I favor an alternative pathway to a sustainable energy system (Linden, 1995, 1996, 1999) based on my confidence in the availability of natural gas as a transition fuel, and in the tremendous promise of high-tech renewable technologies that are inherently inexhaustible, free of pollutants and carbon emissions, and adaptable to distributed generation of electricity and hydrogen. This pathway calls for:

1. Increasing RD&D investments by industry, government, and industry/government consortia in high-tech renewable options such as photovoltaic, solar-thermal, and wind power, and the use of chemically pure electrolytic hydrogen for transportation uses and as an energy storage medium for reconversion to electricity by means of PEM fuel cells or the new reversible PEM fuel cell/electrolyzer systems.

2. Deploying solar and wind power as rapidly as is justified by their fully internalized economics (i.e., giving credit to such positive externalities as elimination of conventional pollutant and carbon emissions and to any benefits derived from the generally distributed nature of these power sources, and debiting the costs of overcoming the problem of the intermittency of these sources).

3. Providing appropriate incentives to industry and consumers for the accelerated conversion of surface transport to electromotive drive. After a possible transitional period in which conventional transportation fuels would be used more efficiently in hybrid systems, the ultimate goal would be to have all surface transport powered by hydrogen stored on board through the use of PEM fuel cells operating in tandem with advanced batteries.

4. To facilitate this conversion of surface transportation, creating a practical, dispersed hydrogen refueling system for light-duty vehicles that delivers compressed, high-purity hydrogen at competitive costs with gasoline or diesel fuel, taking into consideration the higher efficiency and lower maintenance costs of hydrogen-fueled vehicles, offset by the amortization of whatever cost premium such vehicles may require.

5. Over the three to five decades needed to achieve sufficient global market penetration of these zero-carbon-emission technologies, keeping annual global carbon emissions within a range that ensures that total anthropogenic emissions between 1991 and 2100 will not exceed 1,000 gigatonnes and will be in steep decline after 2050. This will be facilitated by such measures as the phaseout of power generation in coal-fired steam-electric plants and a shift to electromotive surface transport. According to the current best estimate of the Intergovernmental Panel on Climate Change, a global carbon budget of no more than 1,000 gigatonnes would limit atmospheric CO_2 concentrations to 550 parts per million by volume at equilibrium, and additional global surface temperature increases to 1°C by 2100 and 1.6°C at equilibrium (Houghton et al., 1996; Linden, 1999).

6. Consistent with this pathway to sustainability, *not* following the Kyoto Protocol for premature carbon emission reductions by just the industrial (Annex I) nations that will be responsible for only a minor share of

projected emissions increases, but instead capping peak global anthropogenic carbon emissions at about 11 gigatonnes per year in the 2030–2050 time frame (Linden, 1999).

7. Using natural gas as the transition fuel to a sustainable energy system because of its inherently low conventional pollutant and carbon emissions, growing global availability, and relatively low cost.

This strategy seems less risky because it makes no a priori assumptions of the final zero-carbon-emission technology mix and logistics of hydrogen supply, and, therefore, does not depend on the extremely favorable economics of converting coal to hydrogen by unproved processes, and the unsubstantiated economics and environmental impacts of carbon sequestration. Investments based on this strategy also appear to be less risky because they are on a much less massive scale than that required for coal supply, hydrogen production, and carbon sequestration complexes supporting 800 MW of central power generation, and because they offer a permanent solution for meeting U.S. and global energy needs without detrimental environmental impacts.

Reducing Reliance on Coal

A major element of this strategy is to rapidly reduce U.S. and, especially, the developing nations' reliance on coal. This can be accomplished by substituting abundant natural gas resources for coal in power production in modular, highly efficient, and low-cost combined-cycle turbine systems which emit negligible conventional pollutants and only one-third as much CO_2 as conventional coal-fired steam-electric plants. During the 30–50 years it would take for zero-carbon-emission renewable or essentially inexhaustible power sources to capture a major share of the global energy market, natural gas would also be a convenient and widely available energy source for efficient combined heat and power (cogeneration) systems using fuel cells, microturbines, reciprocating engines, and combustion turbines with capacities from 5 kW to 50 MW. In addition, natural gas reforming by well-proved, widely practiced, efficient, and low-cost processes would be used as an interim source of hydrogen for transportation fuel needs, in combination with hydrogen produced by off-peak power from whatever source is cheapest. Also, as a fallback strategy, the development and demonstration of inherently safe and proliferation-proof nuclear breeder reactor technologies would be resumed in the United States to ensure the long-term availability of nonpolluting baseload power in case this option proves to be more cost effective.

In parallel with this proposed pathway to a sustainable global energy system, it seems prudent to pursue the fossil fuel reforming/gasification option with carbon sequestration. Intensive R&D to validate the coal-based approach advocated by Williams and to demonstrate its critical elements appears to be well justified. Such issues as the suitability of large, open horizontal aquifers for secure sequestration of CO_2 and the feasibility of deep-ocean disposal are, of course, generic to all fossil fuel decarbonization options and clearly require major RD&D investments. However, early consideration of natural gas conversion to hydrogen near the point of gas production, with sequestration of the CO_2 in depleted gas and oil fields, seems to be indicated. This promises to be the most cost-effective approach to avoiding the release of up to 290 gigatonnes of carbon—the carbon content of the estimated 20,000 trillion cubic feet (Tcf) of remaining technically recoverable global natural gas resources (Linden, 1999). The commercial feasibility has already been confirmed in locations where the CO_2 can be used for enhanced oil recovery and where substantial carbon taxes have been imposed.

A major element of this strategy is to rapidly reduce reliance on coal.

The 20,000 Tcf of remaining natural gas resources (compared to 5,145 Tcf of year-end 1998 proved reserves) would have satisfied 1996 global fossil fuel consumption for only 64 years and would meet projected 2020 requirements for only 38 years. The portion of this resource base that will eventually be economically recoverable is not known, but should be at least on the order of 10,000 Tcf. This excludes the potentially larger unconventional natural gas resources, such as the enormous deposits of natural gas hydrates. In addition, there are as much as 3,000 billion barrels of conventional crude oil and natural gas liquids reserves and technically recoverable resources (i.e., excluding unconventional sources of hydrocarbon liquids such as tar sands and oil shale) which contain roughly another 340 gigatonnes of carbon (Linden, 1999).

In combination with the use of large natural gas reserves and resources, the optimal exploitation of liquid fuels in environmentally acceptable ways—such as for hybrid electromotive transport—should provide the necessary lead time for a shift to a zero-carbon-emission energy system. After all, with an allowable carbon emission budget of up to 1,000 gigatonnes, this strategy should leave ample margin for slower than anticipated progress towards the zero-carbon-emission goal. It should also be noted that, in terms of energy content, global proved reserves and recoverable resources of coal and lignite are six to seven times as large as the corresponding natural gas reserves and resources. However, even this amount of energy would provide only on the order of 150 years of projected global demand via the hydrogen production/carbon sequestration route and is, therefore, by definition, not a sustainable option.

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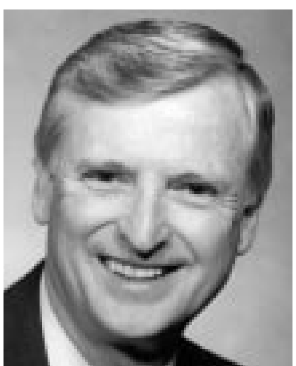
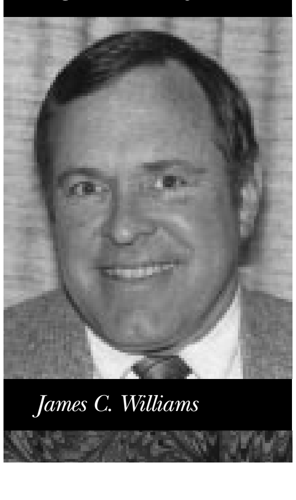
Structural Materials: Challenges and Opportunities

Edgar A. Starke, Jr., and James C. Williams

With the abundance of new structural materials, industrial designers and engineers are faced with an ever-growing number of choices for use in products.



Edgar A. Starke, Jr.



James C. Williams

Recent advances in structural materials have enabled the development of improved products that have a positive impact on our economic competitiveness, national security, and quality of life. Although the general public tends to hear of such advances only in the context of new consumer devices, high-performance sporting goods, or advanced military aircraft, the materials industry makes continual improvements that affect many fields of endeavor. During the last few decades, new analytical tools for examining microstructures, new sensing devices for process control, and improved modeling capability have increased our knowledge base

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and ability to tailor materials to specific applications. The improved materials have led to enhanced performance of many products, often times with a reduction in costs.

With the abundance of new structural materials, industrial designers and engineers are faced with an ever-growing number of choices for use in products. Typically, engineers use three major criteria to select materials:

- desired properties, such as mechanical strength, modulus, plastic flow resistance, fatigue resistance, damage tolerance, corrosion resistance, characteristics under electrical influences, behavior in fire, and environmental impact (toxicity and pollution);
- manufacturing technology available to work with a material, such as casting, machining, forming, etc.; and
- economic viability, including the cost of the material (both initial and over its life cycle), the cost of component production, the availability of the material, and the number of supply sources.

Special requirements have driven innovation in both materials and design.

A product team analyzes these criteria in conjunction with specific performance requirements to determine a product's final configuration and materials content. Some of these decision-making processes are more rigorous than others, but all require constructive interaction between several engineering disciplines.

In recent years, a number of factors have motivated the development and use of improved structural materials and manufacturing processes, including

- demand for new products with unique performance requirements,
- demand for improved performance or extended life of existing products,
- the availability of new manufacturing methods,
- cost reduction requirements, and
- international competition.

This article describes several recent examples of the use of improved structural materials and discusses opportunities for future development.

New Product Requirements

The evolution of aircraft has focused on the need to enhance basic capabilities, including range, payload, speed, and operating cost, all of which have been served by improvements in structural materials (Greenwood, 1989). For example, higher air speeds cause increased frictional heating, which, in turn, raises an aircraft's skin temperature. In response, skin materials have progressed from wood and fabric to advanced alloys of aluminum, titanium, and polymer matrix composite materials containing high-strength carbon fibers. Early aluminum alloy use was hampered by exfoliation corrosion (grain separation due to humid air), but the development of aluminum-clad materials and the use of anodizing resolved this issue. As a result, high-strength aluminum alloys have been the materials of choice for aircraft for several decades. The need to enhance structural efficiency through lower weight led to further improvements in aluminum alloys, many of which were achieved via new manufacturing processes such as double aging, reversion aging, and controlled combinations of heating and mechanical deformation between quenching and aging. These practices, along with tight controls on alloy composition, have increased the strength, durability, and corrosion resistance of aluminum alloys (Starke and Staley, 1996). Today's aluminum alloys are 1.5 times stronger than the early alloys used for aircraft skin and, taking into account inflation, have essentially the same cost.

Similar advances have been made in aircraft engine materials, where demands for more thrust and better fuel efficiency have led to higher operating temperatures, lower engine weights, and increased rotor operating stresses. Nickel-based superalloys and titanium have replaced steel and aluminum, and various processing methods have been developed to directly shape the alloys into components, including forging, investment casting, directional solidification, and single crystal production (McLean, 1995; Williams, 1995).

In military aircraft, special requirements have driven innovation in both materials and design. For example, the B-2 Spirit bomber, developed for the U.S. Air Force by Northrop Grumman, combines a large payload and exceptionally long range with low radar observability, or stealth technology. Able to carry a payload of 40,000 pounds and fly to almost any point on the globe within hours, the B-2 Spirit uses advanced polymer composite materials and special radar-absorbing surface coatings, coupled with its unique geometric design, the flying wing. Further material and design innovations were required to reduce the radar signature of the engine inlets and to minimize the infrared signature of the exhaust. The B-2 Spirit was the first aircraft program where structural materials were selected for their non-structural properties, but this emphasis will become more common in the future.

Early commercial aircraft derived much of their technology content from military programs. Today this is less common, but new civilian aircraft systems still require innovative materials solutions to meet market demands. As anyone who has traveled from the United States to the Pacific Rim on a subsonic flight can attest, the trip is long and tiring. A faster aircraft is attractive for these routes, and market projections indicate that substantial demand exists for high-speed civil transport on such long-range flights (National Research Council, 1997b). Studies show that airplanes capable of flying at Mach 2.0–2.4 and carrying 250 to 300 passengers for distances of at least 5,000 nautical miles could have a market large enough to support development costs and compete effectively with next-generation subsonic aircraft. Meeting the constraints for such an aircraft, including strict noise and emission standards, creates challenges unlike any faced before in commercial aviation, and the engineering solution is not yet clear. However, history shows that engineering responses to such needs inevitably emerge, and the country or entity that provides a viable solution may dominate commercial aviation for a significant period of time.

Performance Improvements

Space programs offer significant opportunities to use new structural materials to improve existing systems. For example, one consideration in building the international space station is the number of space shuttle missions necessary to transport materials and components for its assembly in space. An obvious way to reduce this number is to increase the payload per mission by reducing the weight of the shuttle system itself. Such weight reductions can best be accomplished by increasing the structural efficiency and using stronger, lighter materials. The space shuttle's large expendable cryogenic tank, used to carry the liquid hydrogen rocket engine fuel, was selected as a weight reduction candidate. It has been known for some time that alloying aluminum with lithium decreases the material density and increases the stiffness, but only quite recently have melting and processing methods been developed to put this to practical use. The shuttle's improved hydrogen tank uses a new aluminum-lithium alloy that is 5 percent lighter and 30 percent stronger than the aluminum alloy 2219 of the original tank. In addition, the tank was redesigned to be more structurally efficient. The combination of the new design and the new material provided a 6,800-pound reduction in weight, which translates directly into a comparable increase in the shuttle payload (Wagner, 1998).

New civilian aircraft systems require innovative materials solutions.

Altering specific material properties to optimize a component is a major part of materials engineering. Properties such as stiffness or strength can be enhanced by the controlled introduction of a second phase constituent. The resulting multiphase material derives its properties from both constituent phases, and the combination, or composite, is superior to either component alone. Selective reinforcement of aluminum, titanium, and intermetallic alloys can be achieved with hard, stiff particulates such as silicon carbide, or with monofilaments of boron, silicon carbide, and carbon to obtain performance properties as much as two times better than those of unreinforced alloys.

Titanium-matrix composites containing silicon-carbide monofilaments have been shown to have high strength, stiffness, and thermal stability, and they represent a superior class of materials for use in aircraft components. In aircraft engines, these materials permit the design of smaller, more efficient rotating components and can allow for higher thrust-to-weight ratios. A number of potential applications exist for titanium-matrix composites in military turbine engines (Peel, 1996), but these composites are expensive and must be used selectively to reinforce structural components while achieving a balance between performance and cost. Typically, a numerical factor called the economic trade factor is used to define the additional cost that is acceptable to achieve a pound of weight reduction. For military aircraft the acceptable cost is higher than for civilian applications; even so, the current cost of titanium-matrix composites is prohibitively high. To achieve extensive use, the material costs must be reduced to approximately $500 per pound, down from the current $2,000 to $2,500 per pound.

Cost is less of an issue in the production of sporting goods, where new structural materials can also have a significant impact on performance. In one example, a shape-memory alloy called Zeemet has been specifically developed by Memry Corporation for golf club head inserts (NASA, 1997). Shape-memory alloys have the capability to reversibly change shape with changes in temperature. Zeemet is also superelastic and has high damping attributes that affect the dynamics between the club and the ball. When a Zeemet club insert contacts a golf ball, it undergoes a split-second change in its metallurgical structure, keeping the golf ball on the club face longer and thus supplying more spin. Anyone who has played golf can appreciate the benefit that more "bite" provides in controlling the ball when it lands.

Shape-memory alloys have the capability to reversibly change shape with changes in temperature.

Shape-memory alloys are also used in various medical devices, including stints, which are used to prevent the reblockage of blood vessels after angioplasty. Memry's stints are made from Nitinol, a roughly equiatomic alloy of nickel and titanium. A stint is inserted into the region of the blockage inside the blood vessel where it is then expanded by a balloon. At this point it is in a soft, low-temperature, martensitic condition. Warm (40°C) saline solution is injected into the blood vessel to induce a phase change, stiffening the material. The phase-change temperature has enough hysteresis to prevent the stint shape from transforming back when the body temperature returns to normal.

Another application for shape-memory alloys is an anti-scald device, called MemrySafe. Tap water scald injuries have been cited as the second most common cause of serious burn injuries, often occurring in children and the elderly. With MemrySafe, a valve reacts to the water temperature, reducing the flow if the water becomes too hot and restoring the flow when the water temperature reaches a safe level.

Extending Product Life

Many aircraft operated by the U.S. Air Force are being used much longer than originally intended. Aircraft with a planned lifetime of 10–20 years may remain in service for up to four times as long, and many planes have encountered age-related problems such as fatigue cracking, corrosion, and wear. To ensure continued airworthiness and flight safety, the structural components which have high failure probability must be repaired or replaced (National Research Council, 1997a).

New alloys, materials, and processing technologies, developed since these aircraft were originally designed, are being used to produce better components with significantly lower life-cycle costs. The bulkheads and ventral fins on the F-16 fighter are good examples to illustrate this trend. One of the F-16's three bulkheads supports the vertical stabilizer and typically fails before its specified service life of 8,000 hours. Its material is being replaced with the aluminum-lithium alloy 2097, which has 3 times the fatigue life, 5 percent lower density, and 7 percent higher stiffness than the original material, alloy 2024. Because the replacement alloy is more fatigue resistant, it decreases the frequency and cost of downtime for bulkhead replacement, at an estimated cost savings of over $76.5 million for the F-16 fleet (Austin et al., 1999).

The ventral fins located under the aft section of the F-16's fuselage provide added stability during tight, high-speed turns, and are subject to high stresses from severe buffeting and turbulence. The conventional aluminum-alloy fins fail in less than 400 hours of flight time, and the material is being replaced with a new metal-matrix composite (MMC), an aluminum alloy reinforced with silicon-carbide particles, which is about 50 percent more stiff than monolithic aluminum. The life of the MMC fins is projected to exceed 8,000 hours—more than 17 times the life of the original fins—at an approximate savings of $20.7 million (Austin et al., 1999).

New Manufacturing Methods

Performance-driven applications are often the motivation for introducing new materials and processes. In the automotive industry, two factors drive improvements in fuel efficiency: regulation and competition. Early improvements in fuel efficiency were prompted by government regulation of car manufacturers' average fleet economies. These improvements usually came with an increase in vehicle cost, which can be a disadvantage, especially in the United States where gasoline prices are low and provide little incentive to pay for a more fuel-efficient car.

In 1994 the U.S. government initiated the Partnership for the Next Generation of Vehicles (PNGV), an alliance of government agencies and the three major auto manufacturers. The aim of PNGV is to develop a midsize vehicle capable of getting 80 miles per gallon and meeting current safety and emission requirements. Since weight is a critical factor in determining gas mileage, reducing the weight of structural materials is a major thrust in this program. Based on extensive research by aluminum producers and automobile manufacturers in the 1980s, new technologies enable aluminum cars to meet all of the expectations of today's drivers, yet weigh several hundred pounds less than their steel counterparts. The advantages of aluminum for cars, as for aircraft, are its light weight and high strength-to-weight ratio. When built of aluminum instead of steel, the weight of automotive load-bearing structures can be cut almost in half.

Ford has built 40 aluminum-intensive automobiles based on the Taurus/Sable platform for test purposes, and General Motors recently announced an aluminum-structured electric vehicle. The Audi A8 has an aluminum spaceframe structure that uses formed extrusions which are fusion welded to coupling units made by a high-ductility casting process. The structure is completed with aluminum panels, and all the closures are made of stamped aluminum sheet.

Some of the concerns associated with aluminum car construction include cost, lack of expertise in aluminum design and manufacturing, inadequate repair capability, and public perceptions about the safety of aluminum structures. None of these issues is insurmountable, but each must be addressed as new product development progresses.

Another opportunity for introducing new materials is in biomedical applications such as measuring devices, surgical instruments, and implants. Titanium alloys are often used for joint and long-bone implants because they have lower modulus that closely matches that of bone. Stainless steel or alloys of chromium and cobalt also are used extensively (Fuller and Rosen, 1986).

When built of aluminum instead of steel, the weight of automotive structures can be cut almost in half.

In the case of implants, the primary requirement is biocompatibility, which precludes the use of many familiar structural materials. The ideal implant material would thus be pure titanium, which is chemically inert, but it is too weak when produced by conventional means, and its common alloying elements are potentially toxic. However, researchers at Los Alamos National Laboratory have developed a new manufacturing method for producing nanocrystalline titanium that may replace alloys for bone implants. These ultrafine-grained nanopowder materials are light in weight, 10 times stronger than their conventionally manufactured counterparts, and superplastic, with high formability at certain temperatures. Their strength makes it possible to use hollow hip implants so as to better match the stiffness of surrounding bone (Los Alamos National Laboratory, 1996).

Infrastructure Repair

Another promising application for new materials is infrastructure repair. An estimated 180,000 bridges in the United States are structurally deficient or functionally obsolete, and their repair is costly, time-consuming, and disruptive. However, aluminum's light weight, high strength, durability, and low maintenance requirements offer much promise for rapid, cost-efficient rehabilitation of bridges. One example of its use is the renovation of the Corbin Bridge in Huntingdon County, Pennsylvania. A prefabricated aluminum deck was used to replace the existing steel and asphalt deck, increasing the load limit from 7 to 20 tons (Aluminum Association, 1998). In other examples, wider aluminum decks have replaced narrower ones made of reinforced concrete. Because an aluminum superstructure is lighter, it can be wider and still use the existing bridge foundation. In another innovative application, composite wraps can be placed on the piers and supports of existing bridges for earthquake protection.

Cost Competition and Economic Security

The aerospace industry is critically important to the economic security of the United States, being the largest positive contributor to the balance of payments. Exports for this sector often exceed imports by $25 billion per year. Recently, however, the U.S. commercial aircraft industry has seen its world market share decrease steadily—a cause for significant concern. In response to such concerns, the new Boeing 777 series airplane was developed with a market-driven strategy designed to increase the plane's value.

The future will see a wide variety of new and improved structural materials.

The 777 has many competitive features, including long range, low operating and maintenance costs, and improved reliability, passenger capacity, and fuel efficiency. These features were achieved by combining new materials and design techniques that together contribute directly to the operator's bottom line. To keep fuel and maintenance costs low, the 777 takes advantage of new composite materials and aluminum alloys to decrease weight and improve corrosion and fatigue resistance (National Research Council, 1996). The 777 weighs 6,000 pounds less than earlier midsize plane models. Based on the current fuel price of $0.86 per gallon, this translates to over $1 billion in savings for a typical fleet over its normal lifetime. The engines for the Boeing 777 are the quietest and most fuel efficient ever produced. These engines are quiet because of the large fan diameter, and are fuel efficient because of the higher operating temperatures in the engine and the high bypass ratio of the fan.

The 777 represents an example of a high-technology product that still must compete in the marketplace on the basis of cost. Performance improvement is limited by cost and can only be achieved if the means of performance improvement meets acceptable target cost values. Similar concerns also affect military applications, where increased emphasis is being placed on system affordability due to declining budgets, increased competition for international sales, and the desire to transfer defense technology into the private sector. For these reasons, future materials development activities must achieve both enhanced performance and improved affordability.

Future Structural Materials

The future will see a wide variety of new and improved structural materials. There will be incremental improvements and tailored properties through process simulation and modeling, including functionally graded materials and layered structures. A number of new materials products will become part of the structural materials inventory, including bulk amorphous metallic glasses, nano-structured materials, metallic forms for ultralightweight structures, multifunctional materials, and "smart" materials. There will also be a significant reduction in the time from material development to application due to the use of improved simulation and modeling and scaling from simple experiments. More faithful cost models will also help to determine the viability of manufacturing new materials before the commitment is made to enter R&D scale-up or production.

New structural materials present abundant choices for engineers and industrial designers. The product development cycle will continually become shorter requiring that design, materials, and manufacturing engineering become more fully integrated. The resulting products will be both improved and more affordable.

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NAE News and Notes

NAE Newsmakers

On 12 June 1999, the Institute of Electrical and Electronics Engineers (IEEE) held its annual honors ceremony in London. The following four NAE members were among the award recipients:

B. Jayant Baliga, distinguished university professor of electrical engineering, North Carolina State University, received the IEEE **Lamme Medal** for his sustained, innovative contributions to power semiconductor technology, which have had widespread impact on power electronic systems.

Douglas C. Engelbart, director of the Bootstrap Institute, received the **John Von Neumann Medal** for creating the foundations of real-time, interactive, personal computing, including CRT displays, windows, the mouse, hypermedia linking and conferencing, and online journals.

Akira Ishimaru, adjunct professor of applied mathematics at the University of Washington, received the IEEE **Heinrich Hertz Medal** for fundamental contributions to the theories and applications of wave propagation and scattering in random media and backscattering enhancement.

Lawrence R. Rabiner, vice president of research at AT&T Labs, received the **Jack S. Kilby Signal Processing Medal** for his far-reaching impact on the field of digital signal processing and automated speech recognition through leadership, research, and education.

IEEE also presented two additional awards at the ceremony. **George H. Heilmeier** received the **John Fritz Medal,** sponsored by the United Engineering Foundation, for his discovery of electro-optic effect in liquid crystals, leading to the creation of a new market and industry. The **Elmer A. Sperry Award** was presented to **Bradford W. Parkinson,** on behalf of the Elmer A. Sperry Board, for leading the concept development and early implementation of the global positioning system as a breakthrough technology for the precise navigation and position determination of transportation vehicles.

Floyd Dunn, professor emeritus of electrical engineering, biophysics, and biomedical engineering, University of Illinois at Urbana-Champaign, received the 1998 **Gold Medal of the Acoustical Society of America.** Dr. Dunn was recognized for his fundamental knowledge of ultrasonic propagation in, and interactions with, biological media. The 1999 gold medal was awarded to **Henning von Gierke.**

On 18 June 1999, the U.S. Geological Survey, the National Academy of Sciences/National Research Council, and the Circum-Pacific Council convened a symposium in Washington, D.C., in recognition of **Michel T. Halbouty's** many contributions to the earth sciences on the occasion of his ninetieth birthday. Halbouty is chairman and chief executive officer of Michel T. Halbouty Energy Company, Houston, Texas.

Raymond C. Loehr was presented the **Simon W. Freese Environmental Engineering Award and Lecture** by the American Society of Civil Engineers for significant contributions to environmental engineering in the area of land and waste management alternatives, including bioremediation of sludges and contaminated soil, and for practical applications of research results to solve problems associated with hazardous waste disposal.

Zack T. Pate, chairman, World Association of Nuclear Operations, was honored in July 1999 by the American Society of Mechanical Engineers with the **James N. Landis Medal.** Dr. Pate was recognized for promoting the highest standards of safety and reliability in nuclear power plants and providing educational fellowships and scholarships to more than 2,500 engineering students interested in the nuclear power industry.

Byron D. Tapley was honored as a 1999 **Distinguished Graduate** by the College of Engineering, University of Texas at Austin, where he serves as professor of aerospace engineering and engineering mechanics.

Engineering on Public Television

Last February the NAE, with funding from the National Science Foundation (NSF), brought together a number of engineers, public television producers, and representatives from funding organizations to discuss how to increase and enhance engineering on public television. The NAE's Public Understanding of Engineering program held the workshop as part of a larger effort to better communicate to the public the importance of understanding engineering and its role in societal change. The intent of the workshop was to generate ideas for programs, open lines of communication, and spark collaborations among the three communities. As the groups spoke in turn, it became clear that each had something to learn from the other.

The first panel included four engineers who have long labored to bring engineering to a broad audience. **Samuel Florman,** the workshop chair, discussed the nature of engineering; **Henry Petroski** put engineering in a historical perspective; NAE President **Wm. A. Wulf** spoke on what the public should understand about engineering; and **David Billington** gave an energetic presentation drawing the connection between engineering and social change.

Following the engineers were representatives from three organizations that provide funds to promote public understanding of engineering: Doron Weber of the Alfred P. Sloan Foundation, Charles Freiman and Richard Hirsch of the United Engineering Foundation, and Bill Butcher from NSF. They were followed by a roundtable discussion among public television producers about the types of engineering programs that public television airs and why it makes the choices it does. The session, moderated by Mary Jane McKinven, director of science, natural history, and explorations programming at the Public Broadcasting Service (PBS), included Elizabeth Brock, producer of *Bill Nye, the Science Guy;* Ann Burget, senior analyst for digital strategic planning at the Corporation for Public Broadcasting (CPB); Bill Einrenhofer, the producer who originated the popular *Innovation* series on PBS; Sara Finkelstein, a producer with Production Group, Inc.; Beth Hoppe, director of science programs for WNET; Kenneth Mandel, an independent producer with Great Projects, Inc.; Polly Wells, director of co-production in the department of news, public affairs, and program production at WETA-TV; and Karen Zill of the educational services and outreach department at WETA-TV. Paula Apsell, executive producer of *NOVA* and director of the science unit at WGBH, and Julie Benyo, director of research and development for educational print and outreach at WGBH, joined the workshop by phone from Boston.

The following is a synopsis and synthesis of the day's discussions.

What producers and funders should know about engineering. The engineers at the meeting explained that, although engineering is often confused with science, the two are distinct disciplines with their own bodies of knowledge, their own cultures, and their own ways of solving problems. They want the public to appreciate the attractions of their field, and they feel that increased public understanding of engineering would strengthen our society. Among other things, they would like the public to understand

- the role of the engineer in improving quality of life—that the aim of engineering is to make the world a healthier, more comfortable, more convenient place for people to live;
- that engineering is inherently a rewarding, creative occupation involved in problem solving; and
- the importance of drawing talented students into the field to ensure the future engineering workforce.

Despite its many contributions, engineering has yet to take its place alongside science as a staple of public television programming. There is no *Nova*-like series devoted to engineering subjects, no engineering complement to *Bill Nye, the Science Guy*. This may have something to do with the fact that the engineering profession tends not to produce individuals who come to personify the entire field. Ask a person on the street to name some great physicists, and you'll hear of Albert Einstein and perhaps Stephen Hawking; ask a physics graduate student, and you'll get a slew of others. But ask a graduate of an engineering program to name the greatest engineers of the twentieth century, and you'll get a blank stare. Engineering has few mythical figures or larger-than-life heroes.

What engineers and producers should know about funding. To create a program for public television, a producer must first secure funding, and this is surprisingly difficult for programs on engineering subjects. The natural source of funding for programs on engineering would seem to be large corporations that depend on engineering, but few technology-based corporations are underwriting such programs.

A few institutions actively support engineering programming. The most prominent is the Alfred P. Sloan Foundation, which provides strategic funding for television programs, books, plays, and movies that will improve the public's understanding of engineering, science, and technology. The United Engineering Foundation provides seed money for the initial development of programs and projects, and NSF provides funding for a limited number of engineering-based projects, though usually veiled under the topic of science.

Faced with little support from corporations or other organizations for engineering programming, producers are generally forced to piece together funding from whatever sources they can find. One barrier is that, to avoid any possible conflict of interest, producers cannot solicit funds from corporations that have a direct interest in the topic of a program. Thus, someone developing a show on fuel injection could not go to an automobile manufacturer, even though that would be a logical choice. But that is only part of the problem. In the past, large corporations were more willing to sponsor public television programming that had only indirect benefits for them; now, as the near-term bottom line has become increasingly emphasized, truly philanthropic dollars have dwindled as more funding is tied directly, or indirectly, to the business interests of the corporation. Indeed, no corporations contacted by the workshop organizers were willing to send a representative.

What engineers and funders should know about producing public television. Although the engineers at the workshop initially had the impression that engineering programs almost never appear on public television, the producers explained that engineering gets more exposure than they might expect. They offered a host of examples, including *The Triumph of the Nerds (Parts 1 & 2),* a history of the development of the personal computer; *Twenty-First Century Jet,* a show that described the new Boeing 777; *Escape,* a series about designing devices to help people survive fires, plane crashes, and the like; and *Rescue at Sea,* which detailed a 1909 rescue of two ships that depended on the new communications medium of wireless telegraphy.

These shows, and a number of others, demonstrate that public television is willing to cover engineering topics and that these programs can be done successfully, if only someone undertakes to do them. Producers, PBS, and individual stations can all be expected to be sympathetic to the goal of getting more engineering on the air because educating the public is one of their major goals. However, various professional and practical considerations constrain the types of shows that can be produced. The producers explained that there is no quick and easy way to add more engineering to the public television mix, but they want engineers and funders to understand the following:

- Where do ideas for shows come from? Ideas for public television programs generally begin with an individual producer who will shepherd the show from its conception to its finished form, hiring writers, camera crews, editors, and others to help put it together, but retaining ultimate control over the product. These producers may be employed by public television stations or may be freelancers. Sometimes a station generates an idea for a program or series and then uses a staff producer or freelancer to co-produce it.

- How are ideas put into production? To produce a program one must secure funding for it—from foundations, corporations, government agencies, and individuals—or else it will not get made. Even then there is no guarantee that the program will be shown, so a producer must secure an agreement from a local public television station to broadcast the show. Ideally, the show will be picked up by PBS and distributed.

- What is the role of PBS and CPB? PBS is a private, nonprofit company that serves as a central distribution service for its member stations, funding the creation of programs that it thinks are worthy of being developed. CPB is a private, nonprofit, government-funded organization that funds the development of shows.

- What kinds of ideas get developed into television shows? Producers must always be conscious of what will sell. Public television, as much as it hopes to be educational, is still in the entertainment business, and cannot assume that viewers will watch simply because a program has some intellectual value. Producers will usually not set out to do a program on a particular topic, such as electric cars or genetically modified crops; instead, they look for interesting stories that deal with an important subject. Even if producers start with a certain topic in mind, they will still look around for a good story, because a good story will keep people interested as they learn about the topic.

- Who controls a show's content? In general, a show's funders will know the topic and the general treatment planned by the producer, but they have no control over the final content. Traditionally, engineers have been involved in public television programming as technical advisors. This is an important job, but it can be frustrating, particularly for the engineer with a lot of ideas for a show. Producers will generally have their own concept for a show and may incorporate few or none of the engineer's suggestions. Engineers must understand that they should endeavor to educate the producers as well as possible, but in the end, the producer has final control of the production.
- Is there evidence that public television makes a difference? When shows about engineering are aired, there is some evidence that they actually can affect viewers' interest in and attitudes toward the subject. Studies of those who have watched various science-related programs on public television have found that, six months after watching, the viewers were more likely to seek out magazine articles or books about the subject of the show, or to do something else related to the programming, than if they had not watched the show.

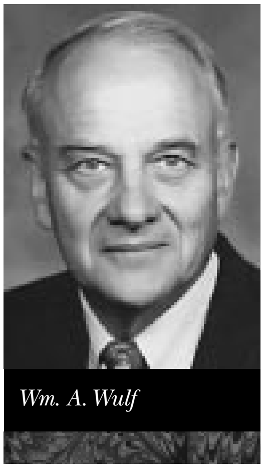
What engineers can do to get more engineering content on public television. The main message that emerged from the meeting is that the engineering and public television communities can both benefit by establishing connections and beginning to work together in various ways.

- For producers already interested in engineering, the best advice is simply to talk to engineers—there is no shortage of stories. The NAE is willing to be a liaison by bringing together producers and engineers as advisors and to generate stories.
- If engineers are to have a broader effect on how their field is portrayed on television, they need to become involved earlier in the process and in ways other than simply checking for accuracy. They can, for example, take the initiative to suggest story ideas to PBS, to public television stations, or to independent producers. In doing so, however, they should remember that their program ideas should have a strong story line with interesting characters; simply claiming that the topic is important won't meet with much success.
- The engineering profession, it was recommended, should place more value on public understanding of engineering. There are few professional rewards for an engineer who spends part of his or her time working with television producers. If engineers want the public to appreciate what they do, they must support those of their number who try to accomplish that.
- Finally, the engineering voice and perspective could be injected into television shows by recruiting some effective spokespersons—experts who can go before the camera and explain engineering concepts succinctly and colorfully, as Carl Sagan did in astronomy, for example.

As a result of this workshop, the NAE has been invited to participate as advisors for several new public television programs. In February 2000, the NAE will poll participants from the workshop to learn about any new productions or collaborations that resulted from the meeting and determine from this evaluation whether to hold similar meetings in the future.

This article is adapted from a summary of the public television workshop written by Robert Pool, a freelance writer. For a copy of the workshop summary, or if you are interested in developing stories for television, radio, film, or print media, please contact Robin Gibbin, director of the NAE's Public Understanding of Engineering program, at (202) 334-1562.

Bringing Diversity to Engineering



Wm. A. Wulf

NAE President Wm. A. Wulf spoke to the Commission on the Advancement of Women and Minorities in Science, Engineering and Technology Development on 20 July 1999. This text is adapted from his testimony.

The NAE believes that diversity in the science, engineering, and technical workforce is critical, and we are concerned with the lack of diversity in the engineering workforce. Engineering is one of those professions that materially affects the quality of life of every person in society. To the extent that engineering lacks diversity, it is impoverished. Since the products and processes we create are limited by the life experiences of the workforce, the best solution—the elegant solution—may never be considered because of that lack!

Women today make up less than 20 percent of students enrolled in engineering, on average, and comprise less than 9 percent of the engineering workforce (National Science Board, 1998). These percentages are much better than they were 25 years ago. Undergraduate enrollment and workforce entries increased steadily through the 1980s to the mid-1990s, but the gains have slowed and in some disciplines have plateaued or declined. This is more serious in light of the fact that the total numbers of young women enrolled in colleges and universities have been increasing steadily the past 10 years. In other words, while the total number of all young women graduating college and entering the workforce has risen in the last decade, the "market share" of young women who have become engineers in the last five years has actually decreased (National Center for Education Statistics, 1997).

Many local, innovative, and inspiring initiatives to recruit, retain, and advance women in engineering have been developed, and those programs have been growing in numbers and effectiveness. Yet even with these programs, the number of new undergraduate enrollees has plateaued. It is a source of great concern to me.

This summer the NAE expanded its programs on women in engineering to include other underrepresented minorities. One program, a direct result of the Summit on Women in Engineering, is the Forum on the Diversity of the Engineering Workforce. This forum will keep attention focused on increasing the numbers of women engineers, and it will create a mechanism for reporting new initiatives and gains among the chief stakeholders.

The Summit on Women in Engineering and the new forum are examples of the NAE's efforts to increase diversity in the engineering workforce. Admittedly, we could have started sooner. Certainly, we have far to go. We see our role not as a program manager but as a catalyst, using the NAE's imprimatur and convening power to bring legitimacy and urgency to the issue and to draw policy-level attention to the solutions.

The diversity of the engineering workforce is a business imperative. The strength of this workforce depends on the availability of talented, well-educated young people available to fill jobs. The quality of the workforce depends on the variety of perspectives and life experiences brought to the job by its members. Without diversity we limit that variety and, as a result, we pay a cost—in products not built, designs not considered, and constraints not understood.

There are many issues that need to be addressed in order to diversify the workforce at large. I would like to focus on one issue that is, if not unique to engineering, at least more serious for engineering than some other professions: the incorrect image that society has of engineering and engineers.

Many people do not have a clear idea of what it means to be an engineer or of what engineers do. A poll commissioned by the American Association of Engineering Societies (AAES) dubbed engineering the "stealth profession" because so few people indicated they knew what engineering was (AAES, 1998). When asked to identify what engineers do, a typical response was "drive trains." The choices made by young women and men, as well as by their parents, teachers, counselors, and role models, are affected by this incorrect image.

A recent study of information technology (IT) professionals commissioned by the Department of Commerce found that sixth-grade students generally identified IT professionals as white male "geeks" (U.S. Department of Commerce, 1997). This study tells us that children, who are developing their internal perspectives of who they can be, have an incorrect or nonexistent image of engineers. It may be that adults—parents, teachers, and counselors—unconsciously reject engineering as a career choice based on the mistaken notions that only men can be engineers and that engineering is boring. Thus, engineering is not offered to young women as a career opportunity, and if it is, it is often accompanied by an incorrect, dull image that must be overcome, not only by the aspiring engineer, but also by all those whose image of engineering does not include young women. Changing this image is a significant challenge, but if the image is corrected, engineering can become more open to women, underrepresented minorities, and persons with disabilities.

I believe more women will enter engineering when they begin to recognize it as a creative, interesting, and rewarding career with the potential to improve people's lives. College programs that increase the numbers of role models and mentors will open engineering up to more women and underrepresented minorities. Employers who elevate the importance of family in the family-work equation, who increase the number of mentors (and train them), and who institutionalize the changes that will advance women, will find that more women enter the workforce and that the women already there will stay longer and work more productively. But programs that support the young engineer are not enough. Challenging the image will require efforts focused on broad sections of society.

Programs to educate the friends, families, teachers, and employers of engineers are few in number, but they may be critical to change. There are no serious attempts to increase awareness of engineering or to correct the image problem. We are all aware of the rarity of engineers presented as interesting, capable people in the print and broadcast media, and in schools, engineering is rarely mentioned in nonengineering curricula. Perhaps, to complement the existing programs, we should work on social change:

- For society at large: Create public service announcements that use the words "engineering" and "fun" in the same sentence.
- For K–12 and college curricula: Develop lessons in which the engineer—and the engineering—is explicit and not subsumed under the terms "science" or "technology." Use engineering to turn students on to math and science.
- For engineering schools: Implement pedagogical methods that keep the educational challenge, but remove the social hurdles that some students, but not all, have to jump over.
- For employers and teachers: Promote academic and industry teams that receive regular training in gender and minority sensitivity.
- For employers: Measure the performance of senior managers and professors against the diversity of the teams they manage.
- For engineering organizations in general: Institutionalize an appreciation for differences in perspective.

The challenge to change the image of engineering was clearly articulated by the participants at the Summit on Women in Engineering. To change the image we must

- insist on long-term commitment to diversify the workforce;
- involve more than just the engineering community (e.g., education, outreach, and government); and
- target not only the potential engineer but also her parents, family, teachers, counselors, friends, and employers.

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Thirteenth CAETS Convocation Held

The thirteenth convocation of the Council of Academies of Engineering and Technological Science (CAETS) was held 24–27 May 1999 in Sophia-Antipolis, France. It was hosted by the Council for Applied Sciences of the Academy of Sciences of France and its president, Dr. Michel Lavalou. The convocation theme was "Technology and Health," and the session topics included imaging technologies; drugs, vaccines, and gene therapy; the food industry and nutrition; and the management of new health effects posed by new technologies. The NAE cochaired the session on biomechanics, prosthetics, and traumatology, which included a presentation by NAE member **Robert M. Nerem,** Georgia Institute of Technology.

Approximately 200 individuals, representing 16 CAETS member countries, attended the lively sessions. During the last afternoon, visits and tours were set up among several sponsoring companies to various high-technology firms in the local area. Social activities included a visit and reception at Agrobiotec (a local technology company), a reception in the Foundation Maeght in Saint Paul de Vence, a welcoming by the Prefecture of Nice, and several local dinners and receptions.

On Friday, 28 May, the CAETS governing board held its annual meeting and reviewed membership applications from Argentina, the Czech Republic, India, and Spain. All were approved and welcomed into CAETS. Two Korean academies have applied for membership, but only one academy from each country is permitted to join CAETS, so the two academies have been asked to decide how best to resolve their representation. The total membership in CAETS is now 22, and there are hopes that many emerging engineering academies will eventually seek membership.

The next governing board meeting is scheduled to be held in Beijing, China, in 2000, and in the following year the CAETS convocation is scheduled for Helsinki, Finland. The United States will host the convocation in 2003. Because of the large number of CAETS members and the possibility of significant growth in the future, the steering committee is planning a meeting early next year to discuss whether CAETS should change its format and become more proactive concerning world engineering activities. One thing to be considered is a continent-to-continent Frontiers of Engineering program, similar to the NAE's successful German-American and Japanese-American programs. Of course, external funding would have to be sought for any such activities.

During the convocation and governing board meetings, thanks and congratulations were given to Steven Anastasion, vice president and secretary of CAETS since its founding, who plans to retire at the end of this year. The NAE has been and continues to be the sponsor and home to this position, and the governing board elected William C. Salmon, former NAE executive officer, to become the new executive secretary. The NAE added its thanks to Steve Anastasion for his tireless work and the growth he helped to foster in CAETS membership.

Greatest Achievements Project Launched

The NAE is pleased to announce a new project entitled "Greatest Engineering Achievements of the Twentieth Century." The project celebrates a remarkable century of progress and innovation, focusing on the significant impact that engineers and engineering have had on the quality of life in the twentieth century.

The Greatest Achievements project is a collaboration between the NAE and a number of engineering organizations. In the first phase of the project, over 60 professional engineering societies have been asked to submit nominations for the greatest engineering achievements of the twentieth century. The top achievements will be selected by an anonymous NAE panel and announced during Engineers Week, 20–26 February 2000. As part of a larger public awareness campaign, this project is meant to stimulate public discussion about engineers and the contributions of engineering. The NAE anticipates many more collaborative efforts to be generated from this project over the next three to four years.

The deadline for engineering societies to submit nominations is 31 October 1999. For more information on the project, see the NAE's website at http://www.nae.edu, or call Robin Gibbin at (202) 334-1562.

NAE Hosts Society Executives

On 3–4 May 1999, the NAE welcomed 72 presidents, presidents-elect, and executive directors of the nation's leading engineering societies to the annual convocation of professional engineering societies. These gatherings of engineering society leaders and NAE officers include informal discussions of national policy issues of concern to the U.S. engineering community. For the past five years, these meetings have been held in cooperation with the American Association of Engineering Societies (AAES). Every other year the first day's program is the AAES Government Affairs Conference, and the evening of the first day is devoted to the AAES annual awards banquet. This year the AAES initiated its **Norman R. Augustine Award** for outstanding contributions to communications with the public about engineering, and Augustine was the first recipient.

The program on 3 May included discussions with Ernest J. Moniz, under secretary, U.S. Department of Energy; Rita R. Colwell, director, National Science Foundation (NSF); and panels on R&D funding, national environmental policy, and the media and engineering. The program on 4 May included a summary of the recent National Research Council (NRC) study on sustainable development by **Robert A. Frosch,** Harvard University; a panel discussion on innovation and the national economy led by **Erich Bloch,** Washington Advisory Group, with Charles F. Larson, Industrial Research Institute, and **Duncan Moore,** Office of Science and Technology Policy; a report on the NAE Summit on Women in Engineering; and a panel discussion on challenges to the U.S. engineering community led by NAE President **Wm. A. Wulf,** with Joseph Bordogna, NSF, Winfred M. Phillips, University of Florida, and **Eugene Wong,** NSF.

From the Home Secretary


Simon Ostrach

Threes

Three, in some ways, is a special number. Many of us appreciate the virtuosity of the three tenors, and we all know that three strikes means you're out. Three is also significant in the Academy complex, now known as the National Academies, because it is the number of distinct institutions that constitute that entity.

The three presidents of the NAS, NAE, and IOM meet regularly to coordinate and direct the activities of their organizations and the NRC. Likewise, the three respective foreign secretaries interact regularly through the Office of International Affairs. Now there will also be three home secretaries. The IOM has recently elected its first home secretary, Harold J. Fallon, dean emeritus of the School of Medicine, University of Alabama. The NAS has just elected R. Stephen Berry, the James Franck Distinguished Service Professor of the department of chemistry, University of Chicago, to serve as home secretary in the office held with great distinction by Peter Raven for many years. We three home secretaries now plan to meet together to identify matters of common interest and concern. Although our institutions' election procedures differ considerably in policy and details, we will exchange ideas and information on many of our common tasks and problems. We hope to find ways to improve our members' understanding of the processes and also to find more efficient and user-friendly ways to conduct elections. For example, we will explore how we can move to an electronic election system and establish compatibility among the three systems. Any suggestions for agenda items for this new trinity are most welcome.

An all-time record number of nominations will be considered for the NAE's 2000 election, the one now in progress. The good news is that of the total of 466 nominations, a record number of them, 298, are new. The flip side is that among the new nominations, almost twice as many candidates are from academia, as opposed to the business sector, and this ratio pertains for all the nominations. Although we have tried throughout the years to address this imbalance, we obviously have not succeeded. Perhaps during the next election, when some of the recommendations of the membership task group on this issue are implemented, the situation will improve. I hope you will keep this matter in mind and make a determined effort to nominate more candidates from the business sector for the next election.

Simon Ostrach
Home Secretary

Predoctoral Fellows Named

Following a nationwide competition, 12 predoctoral fellows in integrated manufacturing and processing have been selected in a program sponsored by the Office of Basic Energy Sciences Engineering Research Program of the U.S. Department of Energy (DOE). The program is administered by the NRC Fellowship Office under the guidance of the NAE, and its goal is to create new manufacturing and processing methods that will contribute to improved energy efficiency, better utilization of scarce resources, and less degradation of the environment. Each fellowship carries a stipend of $20,000 and a cost-of-education allowance of up to $15,000.

The 1999 recipients and the institutions they will attend are: Matthew J. Bono, University of Michigan, Ann Arbor; Anh X. Dang, Georgia Institute of Technology, Atlanta; Ty G. Dawson, Georgia Institute of Technology; Vincent DiFilippo, Tufts University, Medford, Mass.; Krista M. Donaldson, Stanford University, Stanford, Calif.; Chad E. Duty, Georgia Institute of Technology; Russell K. Edwards, University of Utah, Salt Lake City; Dathan S. Erdahl, Georgia Institute of Technology; Carol J. Romanowski, State University of New York, Buffalo; Shadrach J. Roundy, University of California, Berkeley; Andrew J. Scholand, Georgia Institute of Technology; and Brooke S. Stutzman, University of Michigan, Ann Arbor.

Eighty-four fellows have been selected since the program began in 1993. They attend, or have attended, 28 universities throughout the nation. The program emphasizes research in integrated, large-scale manufacturing and processing systems. Related areas of research are unit operations, tooling and equipment, intelligent sensors, and manufacturing systems as they relate to product design. Information on the research plans of all 1999 DOE integrated manufacturing predoctoral fellows, as well as those of the 1997 and 1998 fellows, can be found on the Fellowship Office website at http://fellowships.nas.edu.

Fellows named in 1996 will present their research at a symposium to be held 15 October at the National Academies building. **Deborah S. Nightingale,** senior lecturer, Lean Aircraft Initiative, Massachusetts Institute of Technology, and a member of the NAE, will give the keynote talk.

In Memoriam

PAUL L. BUSCH, 61, chairman, president, and CEO, Malcolm Pirnie, Inc., died on 27 July 1999. Dr. Busch was elected to the NAE in 1996 for contributions to the practice, professionalism, and pedagogy of environmental engineering.

ALBERT P. GAGNEBIN, 90, retired chairman, INCO Limited, died on 14 February 1999. Mr. Gagnebin was elected to the NAE in 1974 for the invention of the process for making ductile iron and contributions to the development of spheroidal cast iron.

ROBERT T. JONES, 89, honorary fellow, NASA Ames Research Center, and professor, Stanford University, died on 11 August 1999. Dr. Jones was elected to the NAE in 1973 for creative contributions to aerodynamics and fluid mechanics, especially to the theory of sweepback for high-speed aircraft wings.

HAROLD L. MICHAEL, 79, professor emeritus, School of Engineering, Purdue University, died on 2 August 1999. Mr. Michael was elected to the NAE in 1975 for leadership in education, research, and practice in the fields of highway traffic engineering, planning, and safety.

ANGUS PATON, 93, former senior consultant, Sir Alexander Gibb & Partners of Reading, England, died on 7 April 1999. Sir Paton was elected a foreign associate of the NAE in 1979 for contributions in the planning, design, and management of international civil engineering projects.

JOHN R. PHILIP, 72, fellow emeritus, Land and Water Commonwealth Scientific and Industrial Research Organization, died on 26 June 1999. Dr. Philip was elected a foreign associate of the NAE in 1995 for contributions to the understanding of multiphase flow in porous media, subsurface hydrology, and geotechnical engineering.

GREGORY E. STILLMAN, 63, professor, University of Illinois, department of electrical and computer engineering, died on 30 July 1999. Dr. Stillman was elected to the NAE in 1985 for discovering the behavior of the discrete donor in gallium arsenide and developing sophisticated methods of characterizing high-purity semiconductors.

NAE Calendar of Meetings

1999

1–2 October	NAE Council
2 October	NAE Peer Committees
3–5 October	NAE Annual Meeting
8 October	NRC Governing Board Executive Committee
14–16 October	Fifth Annual Frontiers of Engineering Symposium, Irvine, Calif.
29 October	Congressional Luncheon
2 November	NRC Governing Board Executive Committee
2–3 November	NRC Governing Board
6 December	NAE Committee on Membership, Irvine, Calif.
7 December	NRC Governing Board Executive Committee
10 December	Congressional Luncheon

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

National Research Council Update

Improving Industrial Environmental Performance

A new report from an NAE committee examines metrics used to assess industrial environmental performance. The report, *Industrial Environmental Performance Metrics: Opportunities and Challenges*, identifies factors needed to improve the measuring and reporting of corporate environmental performance.

As noted in the report, U.S. manufacturers have significantly reduced the harmful effects of industry on the environment in the last several decades, in large part because of government regulations that limit pollution. Consequently, most of the measurements that companies use to evaluate their environmental performance have been developed solely to comply with government-imposed reporting requirements.

Manufacturers now are being challenged to expand coverage of environmental performance beyond the factory gate—“upstream” in a product’s life cycle to include the suppliers of raw materials, and “downstream” to produce more environmentally friendly products. Sustainable development further challenges corporations to account for broader ecological and social objectives in their performance.

The report highlights current and potential uses of a wide range of environmental performance measurements in four major U.S. industries: automotive, chemical, electronics, and pulp and paper. Firms in these sectors cite increased manufacturing efficiency, greater market access, and better relations with shareholders as areas where a competitive advantage can be gained from improved environmental performance.

The committee acknowledged the need for stronger federal coordination to improve the tracking and reporting of environmental performance by corporations. In addition, the federal government should work with industry, state and local governments, and other organizations to develop better methods of ranking the relative health risks of individual chemicals, or classes of them, the report says. It also calls for coordinated efforts to help define appropriate measures that can gauge a corporation’s contribution to sustainable development. Such coordination should enhance the reporting of environmental performance.

As more definitive environmental goals are established, industry sectors and individual companies should more aggressively set, track, and report on their progress in meeting targets, the report recommends. Companies that set goals and commit to tracking and reporting progress often realize rapid improvements in environmental performance.

The best methods and tools to assess environmental impact must be disseminated throughout and across industries, the committee noted. This would be most helpful to small companies, which do not have extensive supply chains for materials or the financial means that large companies have to develop effective measures. The government is in a good position to monitor and distribute these recent advances, the report says.

Publications of Interest

The following publications result from the program activities of the National Academy of Engineering or the National Research Council. Except where noted, each publication is for sale (prepaid) from the National Academy Press (NAP), 2101 Constitution Avenue, N.W., Lockbox 285, Washington, DC 20055. For more information or to place an order, contact NAP online at http://www.nap.edu or by phone at (888) 624–8373. *(Note: Prices quoted by NAP are subject to change without notice. Online orders receive a 20 percent discount. Please add $4.50 for shipping and handling for the first book ordered and $0.95 for each additional book. Add applicable sales tax or GST if you live in CA, DC, FL, MD, MO, TX, or Canada.)*

Advanced Engineering Environments: Achieving the Vision (Vol. 1). Advanced engineering environments incorporate computational, communications, and computer networking capabilities to link participants in manufacturing cycles, including researchers, manufacturers, suppliers, and customers. This report assesses NASA's near-term projects related to developing technologies for these environments, and their use by the current and future workforce. Paperbound, $18.00.

A Vision for the National Weather Service: Road Map for the Future. Reviews modernization efforts of the National Weather Service and recommends strategies to introduce new technologies for improved weather analysis and prediction. Paperbound, $18.00.

Groundwater and Soil Cleanup: Improving Management of Persistent Contaminants. Advises DOE on technologies and strategies for cleaning up metals, radionuclides, and dense nonaqueous-phase liquids, such as solvents used in manufacturing nuclear weapons components. Paperbound, $42.00.

Industrial Environmental Performance Metrics: Opportunities and Challenges. Examines metrics used to assess industrial environmental performance, based on a study of four industries: automotive, chemicals, electronics, and pulp and paper. Recommends ways to improve the measuring and reporting of corporate environmental performance. Paperbound, $54.95.

Measures of Environmental Performance and Ecosystem Condition. Examines indices and measures that are used to assess the environmental performance of industrial operations and ecosystem conditions. Reviews properties of ideal indices, surveys and evaluates families of indices, and identifies needs for new or improved measures. Hardbound, $57.95.

Protecting Nuclear Weapons Material in Russia. Update of a 1997 report on DOE's cooperative programs to upgrade material protection, control, and accountability for direct-use plutonium and uranium in Russia. Paperbound, $18.00.

Review of the Research Program of the Partnership for a New Generation of Vehicles: Fifth Report. Assesses progress made toward development of high fuel economy vehicles. Examines engine technologies, batteries, fuel cells, lightweight materials, emissions control systems, power electronics, and vehicle systems engineering. Paperbound, $32.00.

Securing America's Industrial Strength. Examines improved performance of U.S. industries in the 1990s and considers the role of monetary, fiscal, trade, regulatory, and intellectual property policies. Presents new statistical evidence of trends in public and private R&D expenditures by industry and field of research and outlines future policy concerns. Paperbound, $29.00.

U.S. Industry in 2000: Studies in Competitive Performance. Despite a gloomy outlook in the late 1980s, U.S. industrial performance improved dramatically through the 1990s. This report examines 11 key manufacturing and service industries and assesses changing practices in research and innovation, technology adoption, and international operations. Hardbound, $65.00.

Water for the Future: The West Bank and Gaza Strip, Israel, and Jordan. Discusses opportunities for enhancement of water supplies and avoidance of overexploitation of water resources in the Middle East. Emphasizes conservation, improved use of current technologies, and water management approaches that are compatible with environmental quality. Paperbound, $35.00.