Fall 2014

A PANOPLY OF PERSPECTIVES

The BRIDGE

LINKING ENGINEERING AND SOCIETY

The Importance of Engineering: Education, Employment, and Innovation
Marie C. Thursby

International, Interdisciplinary Education on Sustainable Infrastructure and Sustainable Cities: Key Concepts and Skills
Anu Ramaswami, Armistead Russell, Marian Chertow, Rachelle Hollander, Sachchida Tripathi, Shi Lei, Shenghui Cui, and Ajay Singh Nagpure

Systemic Supply Chain Risk
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Hydrogen and Fuel Cells
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Disposal of US Spent Nuclear Fuel
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Technical Advances for Geologic Disposal of High Activity Waste
B. John Garrick and Carlos A.W. Di Bella

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The
BRIDGE

NATIONAL ACADEMY OF ENGINEERING

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Editor's Note

Ronald M. Latanision (NAE) is corporate vice president of Exponent Failure Analysis Associates.

A Panoply of Perspectives

This issue of *The Bridge* is a composite, with articles on a broad spectrum of issues that I expect readers will find of interest.

- Marie Thursby writes on the importance of engineering education in terms of industrial innovation and describes some subtleties in the supply and demand figures for engineers in the United States. This contribution is based on her presentation at the NAE Annual Meeting in 2013.
- Anu Ramaswami describes a new international education program on sustainable infrastructure and sustainable cities, topics that were of interest to my predecessor as editor in chief and a man I very much admired, **George Bugliarello**.
- Yossi Sheffi and Barry Lynn review trends in industrial vulnerabilities that may increase systemic supply chain risks.
- Yannis Phillis, **Asad Madni**, and colleagues write on the seeming inability of international leaders to take action on climate change.
- Hydrogen and fuel cell technologies may represent a means to environmental, economic, and energy security, but not without the resources to capitalize on these technologies, in the view of Sunita Satyapal.
- A leader in the field of nuclear plant design, **Salomon Levy**, provides a historical perspective and a statement of his thoughts on the disposal of spent nuclear fuel.
- **John Garrick** and Carl Di Bella present an update on technical advances for the disposal of high-level nuclear waste, the focus of our summer 2012 issue.

This seemingly eclectic mix of topics collectively treats many engineering issues that are fundamental to life on this planet and to the global standard of living. The world's inhabitants have fundamental needs—clean air, clean water, a safe and reliable food supply—and their standard of living depends on the quality of their housing and shelter, their health care, and a dependable infrastructure to support economic development in the broadest sense. Many of these topics have been addressed in recent issues and the current contents add to the overall perspective.

With this issue, we are pleased to introduce a new a column that focuses on the role of engineers in the culture of this nation and, indeed, the world. For this inaugural column, Managing Editor Cameron Fletcher and I interviewed Richard Blanco. He is a poet whom our readers may have heard at President Obama's second inauguration—and a practicing, licensed professional (civil) engineer. So when he is described as a PE he acknowledges that the term represents his standing as not only a professional engineer but also a poet engineer. I consider that Richard is an evolving national treasure and I am pleased to introduce this new column with his interview.

I should point out that I was introduced to Richard by one of our members, **Sam Florman**, who is himself an accomplished engineer and writer. Sam is the chairman of Kreisler Borg Florman General Construction Company and the author of seven books, one of which, *The Existential Pleasures of Engineering*, is something of an anthem for liberal engineering education.

Over the years, *The Bridge* has presented timely, thoughtful, and expert discussion of engineering education, research, and practice with emphasis on the role of engineering and technology in society. With this new column, we hope to add context to the reality that engineers not only build systems that are of service to society but also add to our culture in many other ways. Some engineers have been president of the United States. Some are members of Congress. Some engineers are remarkable authors. I myself sing and dance (so to speak . . .) in cabarets that raise funds for my town hospital! We are planning future interviews for this new feature.

The next issue will cover international perspectives on big data. With an introduction to *The Bridge* from **Dan Berg**, guest editor Yong Shi, of the Chinese Academy of Sciences, has enlisted authors from the United States, Asia, the European Union, South America, and Australia to convey trends and developments in this fast-moving area. The spring 2015 issue will present selected papers from the September 2014 Frontiers of Engineering symposium.

As always, I welcome feedback from our readers. Please send your comments to me at rlatanision@exponent.com.

To realize engineering's potential in innovation, US universities will need to extend the "integrative" expertise of engineers into areas well beyond the technical core.

The Importance of Engineering

Education, Employment, and Innovation

Marie C. Thursby is Regents' Professor and Hal and John Smith Chair of Entrepreneurship in the Scheller College of Business at the Georgia Institute of Technology.

Marie C. Thursby

Technological innovation has long been the key to US growth and prosperity, and engineering has been an important driver of this innovation. Indeed, the development and institutionalization of the engineering disciplines in US universities provided much of the talent behind US domination of world markets during the 20th century (Rosenberg and Nelson 1994). Engineering disciplines integrate scientific principles with practically oriented research, providing systems and processes that themselves create ways of acquiring new knowledge. This integration makes engineering critical to successful industrial innovation.

It is therefore sobering to see the low percentage of engineering degrees awarded in US universities today: only 4.4 percent of the undergraduate degrees awarded in the United States are in engineering, compared with 13 percent in European countries and 23 percent in key Asian countries (NAE 2014). Furthermore, with ever increasing economic development and growth worldwide, it is not clear that the best engineers will want to work

This article extends the comments and perspective presented by the author for the panel on "The Importance of Engineering for the Prosperity and Security of the United States," at the 2013 annual meeting of the National Academy of Engineering. Where possible the data have been updated. The author is grateful to Paula Stephan and Jerry Thursby for insightful discussions, and to Stephan for providing data she compiled from doctoral surveys.

in the United States—or that the best employment opportunities for US-educated engineers will be in this country.

Survey evidence from a large sample of R&D-intensive companies headquartered primarily in the United States and Europe shows that firms do not feel constrained to locate new research facilities at home (Thursby and Thursby 2006a). Only 15 percent of those surveyed located all of their R&D at home, and 20 percent conducted more than half of their R&D outside of their home country. Many of them located facilities in developing countries, and the second most important reason for companies' choice of location was access to quality research personnel (Thursby and Thursby 2006a,b).[1]

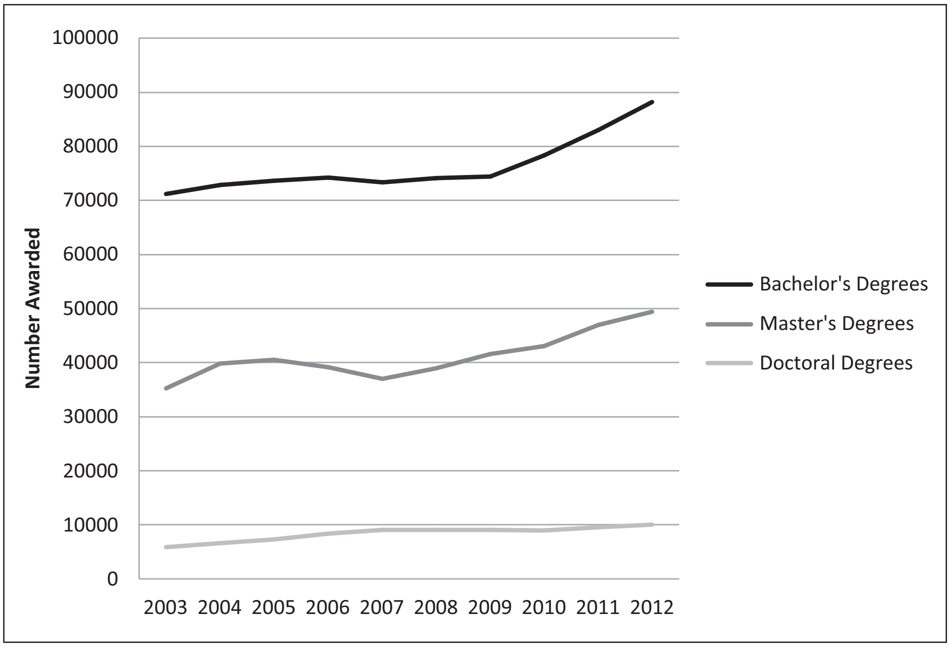

FIGURE 1 Engineering Degrees Awarded in the United States, 2003–2012. Source: Data from Yoder (2013).

Against this backdrop, it is difficult to evaluate the low percentage of engineering degrees being awarded in the United States. Are too few engineering degrees being sought and awarded? The figures cited above compare degrees across countries, but what are the trends in the United States? What are the occupations and employment opportunities for US-trained engineers?

This article presents evidence that, despite the low number of degrees awarded, the US production of engineers at both undergraduate and graduate levels has increased quite dramatically over time.

Engineering Degrees Awarded in the United States

The number of engineering degrees awarded in the United States has increased at all levels since 2003. As shown in Figure 1, the number of bachelor's degrees awarded increased by 40 percent between 2003 and 2012, with 88,176 degrees awarded in the latter year. Master's degrees increased over the same period by 24 percent. In terms of percentage growth, the increase in doctoral degrees awarded was the most dramatic: 71 percent.

The number of doctoral degrees awarded is particularly salient in terms of engineering's role in innovation: engineering PhDs are among the highest ranked in terms of both average number of patent applications and patents granted in 2003–2008 (NSB 2014). Among doctorate-level engineers in the workforce, 84 percent reported in 2010 that their primary job responsibility was basic research, applied research, design, or development.

Figure 2 shows the production of PhDs in nine science and engineering fields over the past 90 years. Two messages are clear. First, science and engineering PhD production has increased fairly steadily since 1945. Not coincidentally, this was the year of Vannevar Bush's report *Science: The Endless Frontier*, which pushed for federal government support both for basic science research and for doctoral students to build the scientific workforce (Stephan 2012). Second, the increase in engineering PhD degrees awarded is remarkable, outpacing all other fields except the life sciences.

Since the early 1990s, however, there has been growing concern over an apparent oversupply of PhDs. Figures 3 and 4 show the percentage of PhDs who graduate with definite employment or postdoctoral commitments for the period 1992–2012. As shown in Figure 3, none of the science and engineering fields had more

[1] The most important reason for locating in a developing country was growth potential of the market.

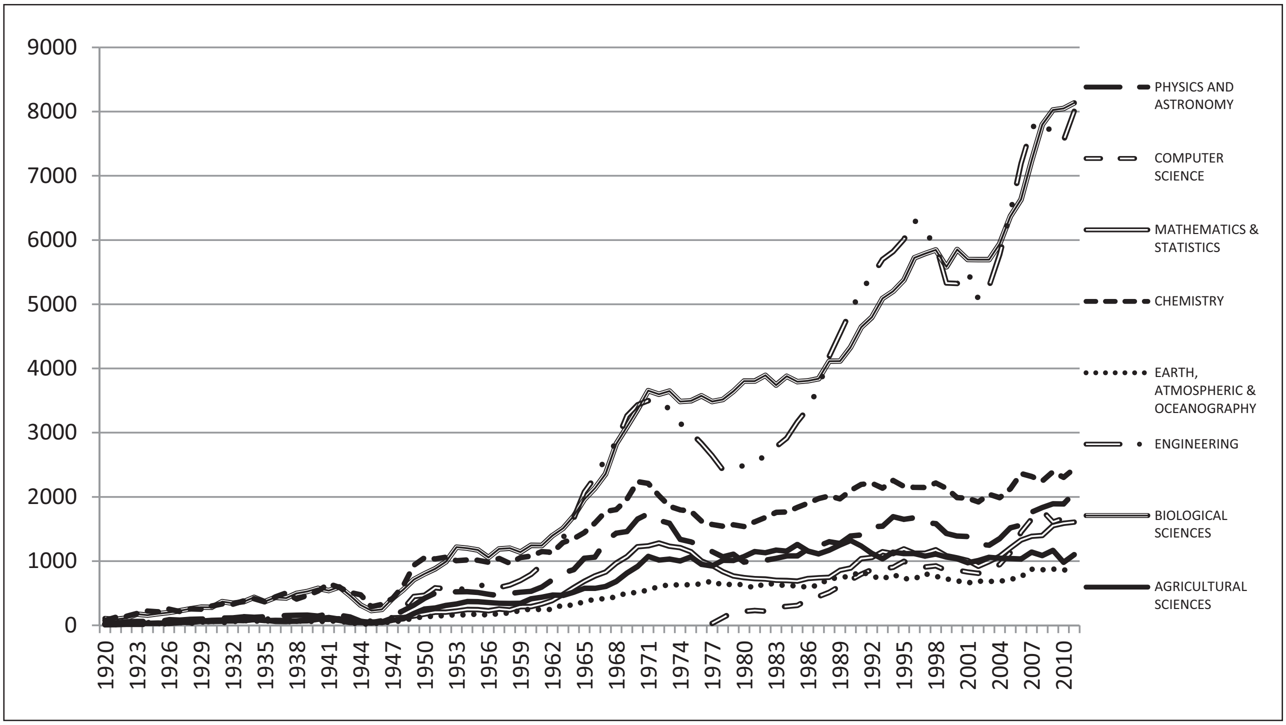

FIGURE 2 PhD Production in the United States, 1920–2011. Source: Stephan (forthcoming).

than 77 percent definite commitments of employment. Moreover, a significant portion of these commitments are for short-term postdoctoral training fellowships rather than industrial or academic tenure track positions (Figure 4). In 2012 two-thirds of the commitments in the life sciences were postdoctoral positions, followed closely by the physical sciences. The picture was a little less bleak for engineering—35 percent in 2012. These trends are troubling because postdoctoral positions are temporary and typically pay less than tenure track academic or industry positions.

Projected Job Opportunities: Beyond Engineering Occupations

Looking forward, projected employment in engineering occupations is not as optimistic as for other science fields or nonscience and engineering fields. Figure 5 shows that the projected increase in engineering

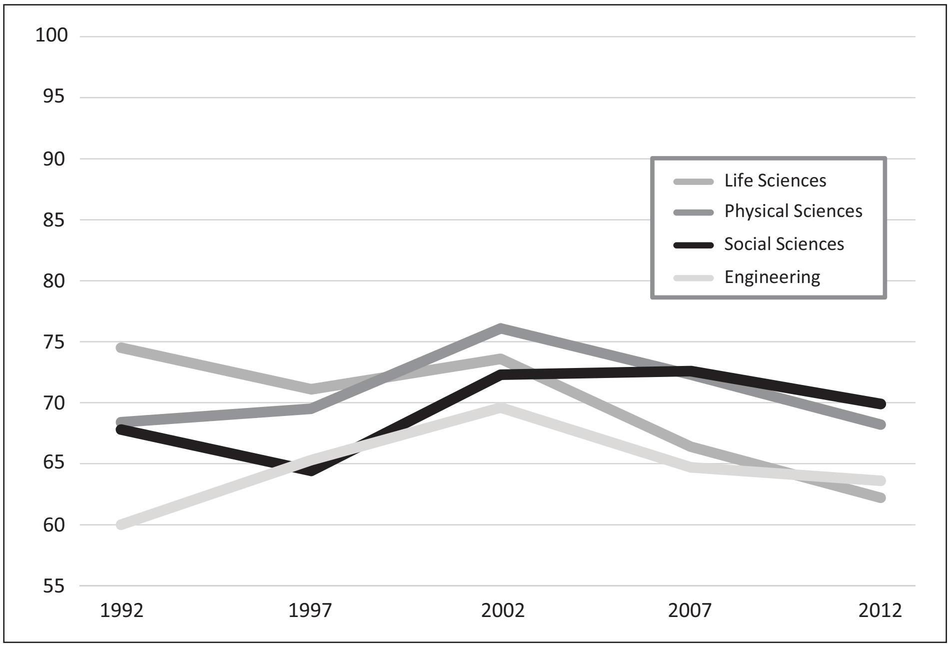

FIGURE 3 Percent of PhD Graduates with Definite Commitments, 1992–2012. "Definite commitment" refers to a doctorate recipient who is either returning to predoctoral employment or has signed a contract (or otherwise made a definite commitment) for employment or a postdoc position in the coming year. Source: NSF (2014).

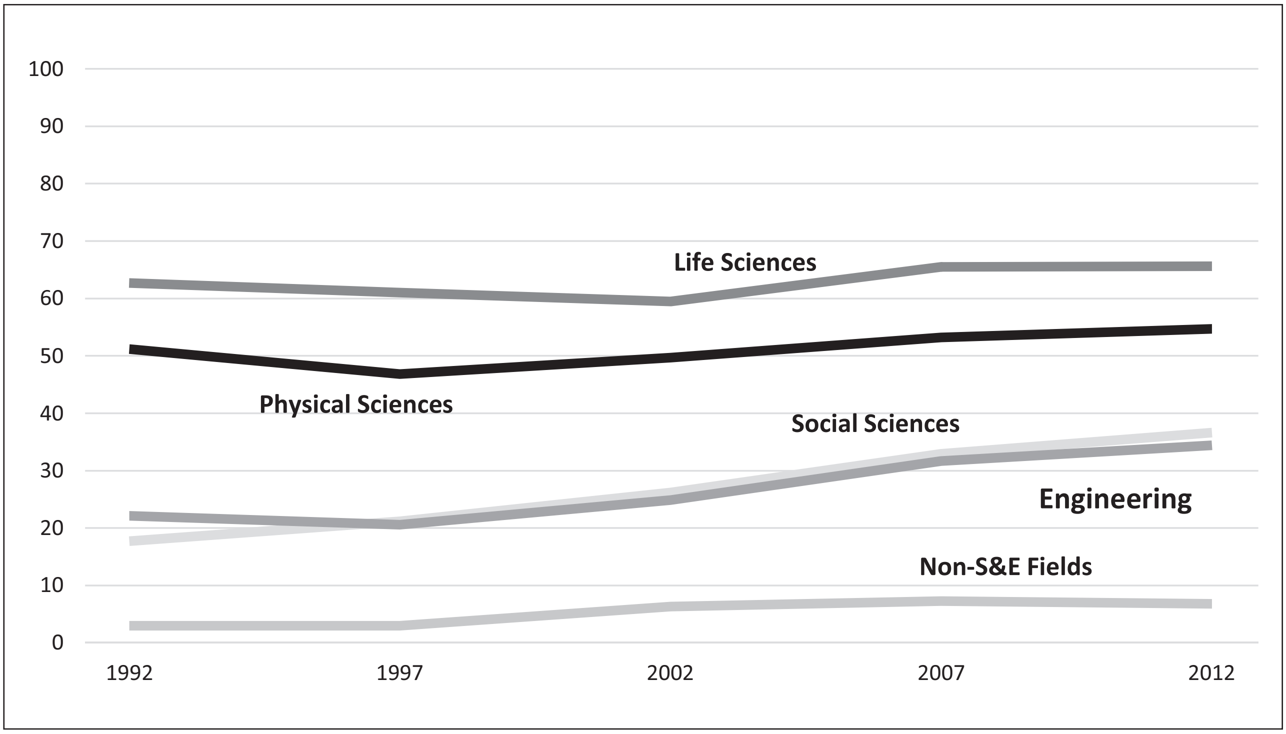

FIGURE 4 Percent of PhD Graduates with Definite Commitments Taking a Postdoctoral Position, 1992–2012. Source: NSF (2014).

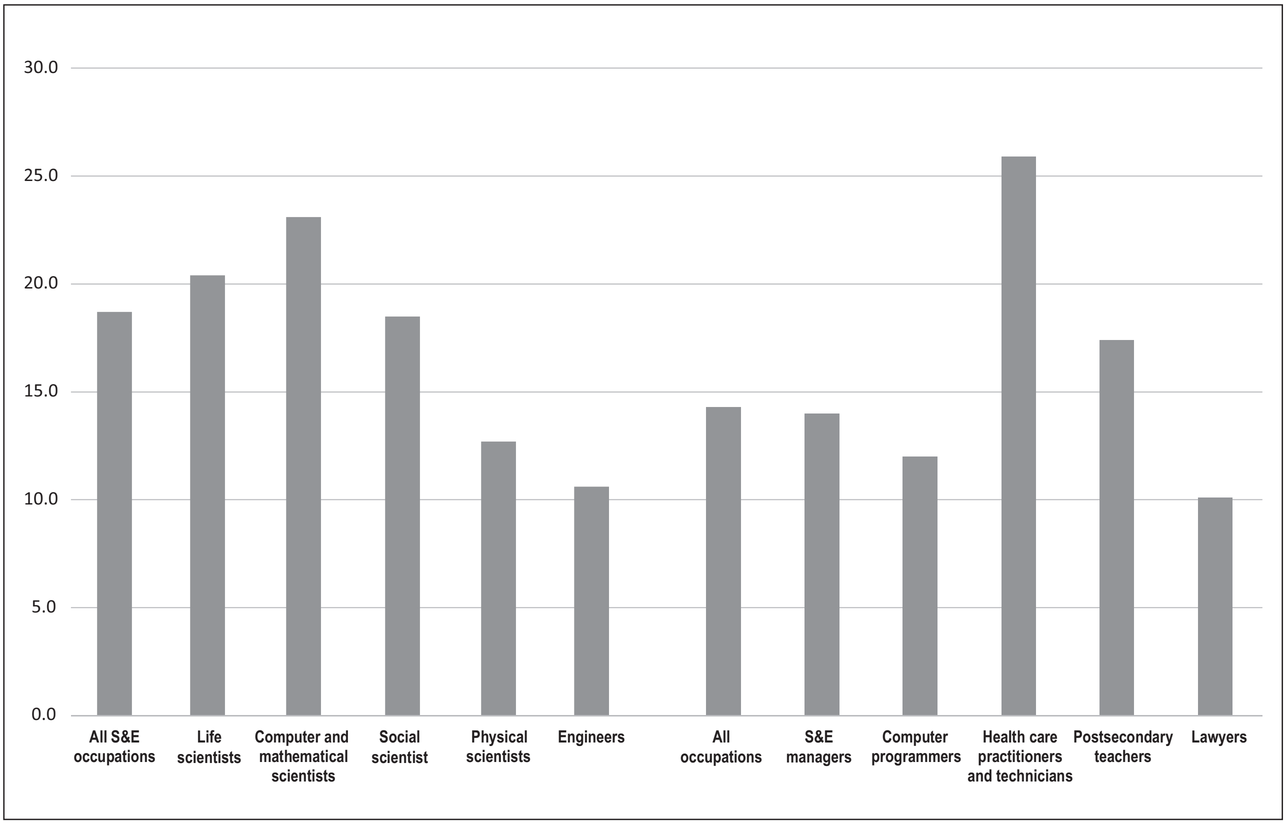

FIGURE 5 Projected Increases in Employment, 2010–2020. Source: NSB (2014).

employment (for all degree levels) between 2010 and 2020 is less than that for other science and engineering fields.

But to assess the importance of engineering, it is necessary to look beyond engineering occupations. Consider, for example, the ultimate management position, that of a CEO. Many CEOs have engineering backgrounds. As one executive put it, "engineering gives you the mindset of solving problems," as well as the technical skills to evaluate many types of data and situations. This example is not rare. In fact, the majority of people whose highest degree is in science or engineering work in jobs outside of their degree field.

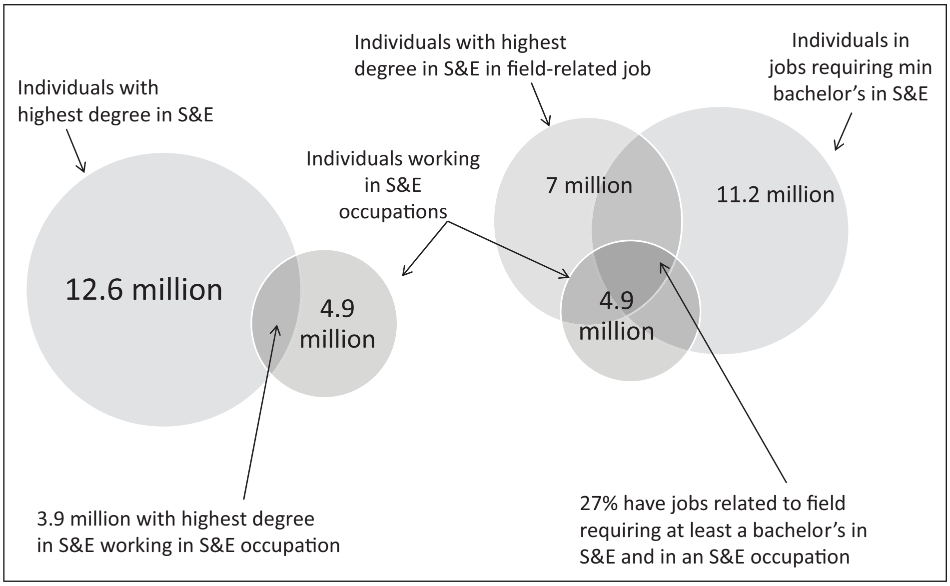

FIGURE 6 Relation of Jobs and Degrees, 2008. Source: NSB (2012).

Figure 6 shows that of the 12.6 million people whose highest degree was in a science or engineering field, only 3.9 million worked in science and engineering jobs in 2008. Of the 11.2 million people whose job required bachelor's-level technical skills, only 27 percent actually worked in science and engineering occupations and 40 percent either worked outside of science and engineering or their highest degree was outside of science and engineering. Common examples of the latter are managers or lawyers with MBAs or JDs whose undergraduate degree was in engineering. Note, however, that 7.9 million of those whose job requires bachelor's-level technical skills work in areas closely related to their field.

Educational Challenge

The employment pattern shown in Figure 6 is not idiosyncratic but rather reflects general trends since the 1990s. This is good news because it suggests that engineers contribute well beyond their technical skills. But it also means that US universities face a major challenge: the need to design curricula to attract and prepare students for the current and future workplace, where the need for multidisciplinary skills is increasingly the norm.

The multinational firm survey mentioned above provides compelling evidence that engineers working in R&D-intensive firms will likely work on globally distributed teams (Thursby and Thursby 2006a,b), and data on the role of teams in innovation show that research teams are becoming ever larger and cross-institutional in nature (Wuchty et al. 2007). Thus engineers managing or working in R&D will need to work across many organizational structures.

The challenge for universities is to design programs that retain the rigor of engineering while broadening the curriculum to address communication across cultures, management within and across organizations, intellectual property and technology transfer issues, financing innovation, knowledge of regulatory environments, and so on.

Many US universities have stepped up to the challenge. At the undergraduate level, some have created "four plus one" programs that introduce cross-disciplinary courses or certificate programs in the fifth year. Others have introduced minors in entrepreneurship or management of technology, and a number of joint degree programs combine engineering with law and/or business. In addition, a number of universities are partnering to meet the challenge. For example, a graduate certificate program at Georgia Institute of Technology and Emory University teams PhD candidates in science and engineering with business and law students to focus on issues involved in commercializing fundamental research.

Concluding Remarks

This article began by recalling the heart of the engineering disciplines—the integration of ideas and techniques that make engineering so essential for industrial innovation. It is fitting, then, to end on a similar note. Engineering holds great potential for continued US innovation in the future. But to realize this potential, it will be necessary for US universities to extend the "integrative" expertise of engineers into areas well beyond the technical core.

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We present an international, interdisciplinary lecture-fieldwork course that trains students to address the challenges of developing environmentally sustainable and healthy cities.

International, Interdisciplinary Education on Sustainable Infrastructure and Sustainable Cities

Key Concepts and Skills

Anu Ramaswami, Armistead Russell, Marian Chertow, Rachelle Hollander, Sachchida Tripathi, Shi Lei, Shenghui Cui, and Ajay Singh Nagpure

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This paper presents the development, delivery, and assessment of an interdisciplinary education program on Sustainable Infrastructure and Sustainable Cities offered to cohorts of graduate students from the United States, India, and China. Developed by an interdisciplinary team of university instructors from the three countries, the curriculum explores how the interaction of engineered infrastructures with social and natural systems shapes urban sustainability outcomes pertaining to resource management, environmental pollution, climate change, and public health. Five key concepts and skills form the foundation of the curriculum: (1) sustainable urban systems concepts; (2) interdisciplinary systems thinking and teamwork skills; (3) intercultural skills; (4) fieldwork, including community-based interactions; and (5) knowledge of ethics in interdisciplinary and intercultural settings

The curriculum is designed for students from six disciplines: engineering, industrial ecology, environmental sciences and climatology, urban planning, public health, and public affairs. An innovative, hybrid lecture-plus-fieldwork format is delivered in several cities in each country, exposing the students to multiple cultures and diverse learning experiences.

Most current infrastructure systems are unsustainable, together being responsible for 95% of US greenhouse gas emissions and more than 10 million premature deaths worldwide.

Background

Impacts of Rapid Urbanization

The year 2009 heralded a historic shift as, for the first time in human history, records showed that more than half of the world's people lived in urban instead of rural areas. And the urban share of the world's population is projected to increase to about 70 percent by 2050, with the urban population almost doubling from approximately 3.4 billion people in 2009 to more than 6.3 billion (UNEP 2009). Rapid urbanization is changing not only the landscape of individual cities but the Earth system itself—and the human experience.

Engineered infrastructures—defined broadly as the systems that supply water, energy, food, transportation, sanitation, buildings (shelter), and public spaces (such as parks, pavements, seawalls) (Chavez and Ramaswami 2013)—are critical to human well-being and economic development in cities. Unfortunately, most current infrastructure systems are unsustainable: they are responsible for more than 95 percent of US greenhouse gas (GHG) emissions and water withdrawals (EPA 2005; Kenny et al. 2009) as well as over 10 million premature deaths worldwide annually as estimated by the Global Burden of Disease (GBD) project[1] (Lim et al. 2012). GBD data show that indoor and ambient air pollution, primarily from energy and transportation, rival childhood underweight among the largest contributors to premature death (Lim et al. 2012).

Furthermore, health effects are exacerbated in cities, where people, resource demands, and pollutant emissions are concentrated spatially. And wide disparities in infrastructure, literacy, and socioeconomic status among different urban populations (e.g., migrant workers and slum dwellers) further contribute to negative health outcomes.

Effectively designing and managing infrastructure to accommodate the current and future needs of cities (e.g., by addressing aging infrastructure in developed cities and rapid demand in newly developing cities) is a critical challenge that will shape global and regional environmental sustainability as well as public health in cities worldwide.

The Need for International and Interdisciplinary Education

An integrated systems approach toward urban planning, infrastructure design, environmental assessments, public health, and public policy has the potential to address the current and emerging challenges of urban infrastructure. A recent review of experiments in infrastructure design and policy in 100 cities around the world illustrates the potential of such efforts (Broto

[1] This activity of the World Health Organization has provided comprehensive estimates of the health effects of diseases since 1990. Information is available at www.who.int/healthinfo/global_burden_disease/.

and Bulkeley 2013), highlighting the need to educate and train professionals from diverse disciplines to address the challenges (Frumkin et al. 2004).

We have developed an international and interdisciplinary curriculum on sustainable infrastructure and sustainable cities for students from China, India, and the United States with backgrounds in engineering, industrial ecology, environmental sciences and climatology, urban planning, public health, and public affairs. The curriculum is built on an interdisciplinary social, ecological, and infrastructural systems (SEIS) framework for developing environmentally sustainable and healthy cities (Ramaswami et al. 2012, 2014). The framework has a strong engineering foundation, focusing on the role of infrastructure and how it interacts with social and natural components.

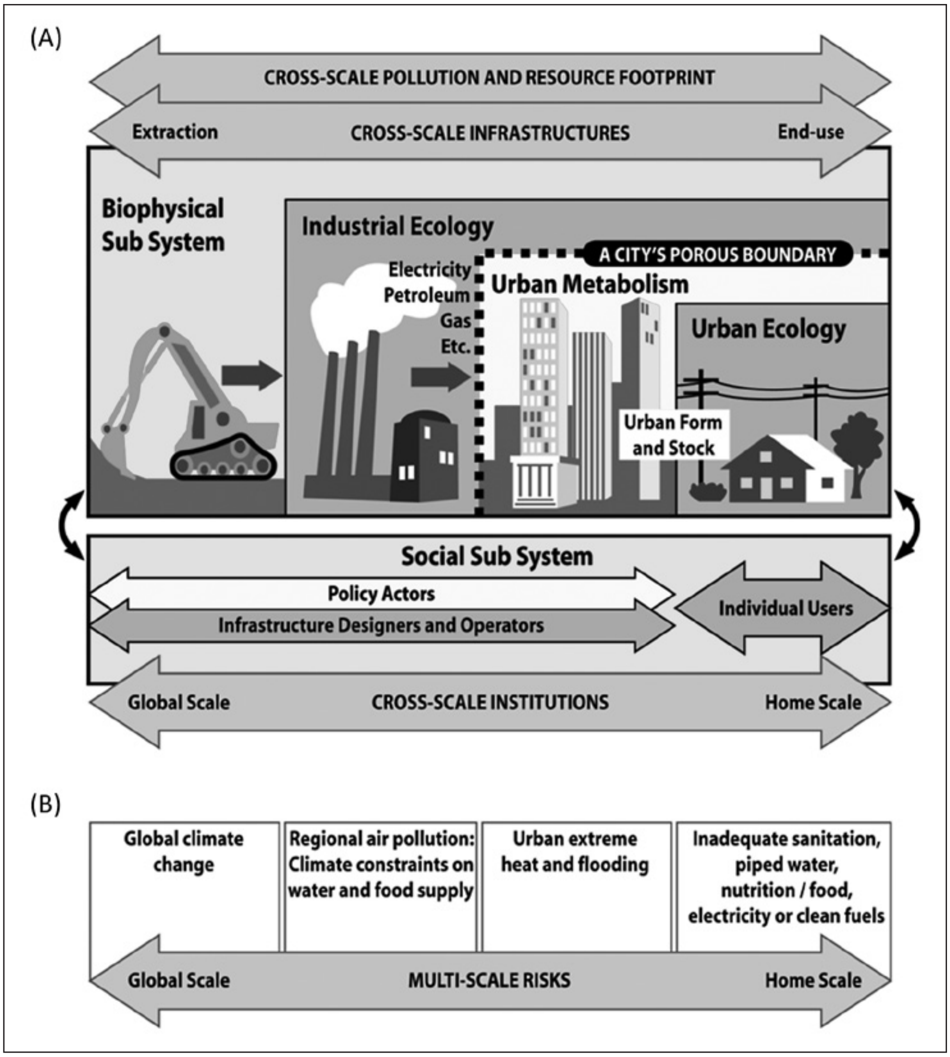

FIGURE 1 Schematic of the social-ecological-infrastructural systems (SEIS) framework, illustrating (A) environmental sustainability of cities: Cross-scale impact of infrastructures on the environment (biophysical subsystem) shaped by people (actors) and institutions interacting across spatial scale in the social subsystem; and (B) multiscale health risks to people in cities from infrastructure-environment interactions across scale. Source: Ramaswami et al. (2014).

A Systems Approach to Designing and Managing Urban Infrastructures

The SEIS framework shown in Figure 1 illustrates a number of 21st century challenges in designing and managing urban infrastructures for sustainability outcomes.

First, although resources were plentiful in the 19th and 20th centuries, local, regional, and global resource constraints loom large in the 21st century, affecting the provision of food, water, electricity, and land for cities (e.g., Bai et al. 2014). Second, the nexus of water, energy, and food is critical—water is necessary for energy and food/agriculture, and energy is needed to supply water and fertilizer for food—and amplifies dependencies and scarcities in the three sectors (Bazilian et al. 2011). Third, in a highly globalized world, trade both among cities and between cities and the hinterland is so intertwined that much of what a city requires in terms of its basic needs for water, energy, and other goods depends on complex transboundary supply chains; for example, food, freight (e.g., goods movement), and electricity travel more than 1,400, 600, and 150 miles, respectively, in the United States (Ramaswami et al. 2012).

Understanding Cities in Context

To address the environmental sustainability of cities, it is imperative to understand the physical environs of a city as embedded in both the greater biophysical system (e.g., large-scale engineered infrastructures such as electric grids, water supply and transportation networks) and the surrounding natural systems (e.g., watersheds, airsheds, and the global atmosphere; Figure 1A).

Infrastructure-environment interactions generate multiple risks at different scales—local, regional, and global—that affect the health of people in cities (Figure 1B). Human health risks are associated with inadequate infrastructure in homes (e.g., lack of water and sanitation in large urban slums in Asian and African cities); extreme heat and flooding at the city-scale exacerbated by poor design of community-scale infrastructure (e.g., concrete pavements, lack of trees and open spaces); pollution of local and regional air, water, and soil from energy, water, and sanitation sectors; and global climate change impacts that can threaten regional food and water supplies. Further, pollutants at one scale can exacerbate pollution at the other scales.

This embeddedness and interaction of risk factors must be taken into account in efforts to address public health in cities.

Interdisciplinary and collaborative approaches are needed to address the challenge of developing sustainable infrastructure for sustainable cities.

Role of Governments, Actors, and Policy Instruments

Because of the embeddedness of cities, local governments alone are unable to manage either the range of relevant infrastructures or their impacts across scale. Nor is it effective to address each sector independently in individual departmental silos, since water, energy, air, transportation, public spaces, urban buildings, and sanitation are all inherently and intricately interrelated, from their common intersection points in cities to their linkages along the supply chains that serve the cities. Integrated urban spatial planning and environmental policies are needed to coordinate across the home, neighborhood, city, regional, and global scales, as illustrated in the social subsystem shown in the bottom part of Figure 1A.

To that end, governments at all levels are increasingly leading multisector collaborations that engage a number of actors—businesses, nongovernmental organizations, and communities—to achieve environmental sustainability and public health goals. In terms of policy design, demand-side management is now becoming as important as supply-side management and cleaner production. As a result, policy instruments to manage infrastructures are evolving beyond "command and control" pollution regulations and infrastructure construction codes to include innovative voluntary programs that engage households, businesses, and infrastructure designer-operators in resource efficiency, conservation practices, and innovative enterprises such as bike and car sharing programs, urban farms, and local food markets.

Curriculum, Learning Objectives, and Methods

The complexity of the challenges described above requires highly interdisciplinary and collaborative approaches to support the development of sustainable infrastructure for sustainable cities. Use of the SEIS framework can enhance understanding of the linkages among engineered infrastructures, environmental sustainability, public health, and the people who use, design, manage, and regulate the infrastructures toward various goals. This understanding can in turn advance learning about how different geographies, infrastructure conditions, regional resource constraints, sociocultural norms, and administrative and political systems shape the design and management of infrastructures for sustainability and health.

What can and should be covered in an international and interdisciplinary curriculum that seeks to educate students about the challenges of developing environmentally sustainable and healthy cities? Our team, including the authors and additional collaborators from the University of Colorado Denver and the National Center for Atmospheric Research, has developed and pilot-tested a six-week summer school on Sustainable Infrastructure and Sustainable Cities. Held in India (2013) and China (2014), with a US session planned in 2015, the program brings together Indian, Chinese, and US students to engage in education and field research in multiple cities in these three countries.

Based on the SEIS framework and on pedagogy drawn from diverse sources and synthesized in an April 2013 workshop,[2] the authors identified five learning objectives for program students:

- Knowledge and understanding of sustainable urban systems concepts;
- Interdisciplinary systems thinking and teamwork skills;
- Intercultural skills;
- Field research, including community-based work; and
- Knowledge of ethics in interdisciplinary and intercultural settings.

We briefly describe each objective, review the resources used to promote learning, and then present early results from qualitative and quantitative evaluations that illustrate the impact of the program on students.

Sustainable Urban Systems Concepts

Sustainable urban systems concepts[3] are drawn directly from the SEIS framework shown in Figure 1 and cover the following topics:

- General concepts such as rapid urbanization, human capabilities, and health and well-being and their association with infrastructures and scarce resources.
- Methods and models to quantify the in-boundary and transboundary environmental impacts of infrastructures. Students learn the use of material-energy stocks and flow analysis, supply chain tracking, and lifecycle assessment to characterize the coupled water, energy, pollution, and GHG emission footprints of urban infrastructure (Figure 1A), thereby providing a baseline measure of a city's environmental sustainability.
- Methods and models to represent multiple risks posed to cities by infrastructure-environment interactions, characterizing mortality and morbidity from inadequate infrastructures (e.g., lack of water, sanitation), hazardous or polluting infrastructures (e.g., accidents and pollution associated with energy production, transportation, and industry), and climate extremes such as heat and flooding (Figure 1B).
- High-impact infrastructure design strategies that promote sustainable consumption and sustainable and cleaner production (e.g., of water and energy); integrated urban spatial planning that enables linkages and synergies across infrastructure sectors (e.g., industrial "symbiosis" for the beneficial exchange of resources among collocated industries and municipal utilities; Figure 2); medium-density mixed-use neighborhood design with efficient transportation systems; and integrated water infrastructure connected with "urban farms" and green spaces. Many of these interventions enhance both environmental sustainability and human health, an intersection that can be captured in the SEIS approach.
- Social and institutional factors that promote or inhibit the adoption of sustainability strategies, such as values, beliefs, and social networks that stimulate individual and corporate behaviors supportive of the environment and health; institutional arrangements such as the formation of regional transportation districts that enable cross-scale management of infrastructures and their impacts; and considerations of power and politics that shape the behavior of policy actors in implementing such changes.

Integrated field experiences are a powerful way to link across disciplines and promote intercultural and interdisciplinary competence as well as ethical awareness.

Students' proficiency in using these concepts is tracked before and after the summer school to assess their skill levels along Bloom's taxonomy continuum, ranging from knowing to understanding to application/synthesis and analytic capacity related to each concept. For example, assessments reported in Ramaswami et al. (2012) show that among a cohort of 26 students drawn

[2] "Sustainable Cities and Interdisciplinary International Education: A Workshop on Core Knowledge and Skills" was hosted by the National Academy of Engineering in Washington on April 24–26, 2013. The workshop objectives, agenda, and speaker presentations are available at www.nae.edu/Projects/CEES/57196/70831/PIREworkshop.aspx.

[3] We have identified more than 40 urban systems concepts that constitute a basic vocabulary across disciplines that address the major topics presented here. Details are provided in Ramaswami et al. (2012).

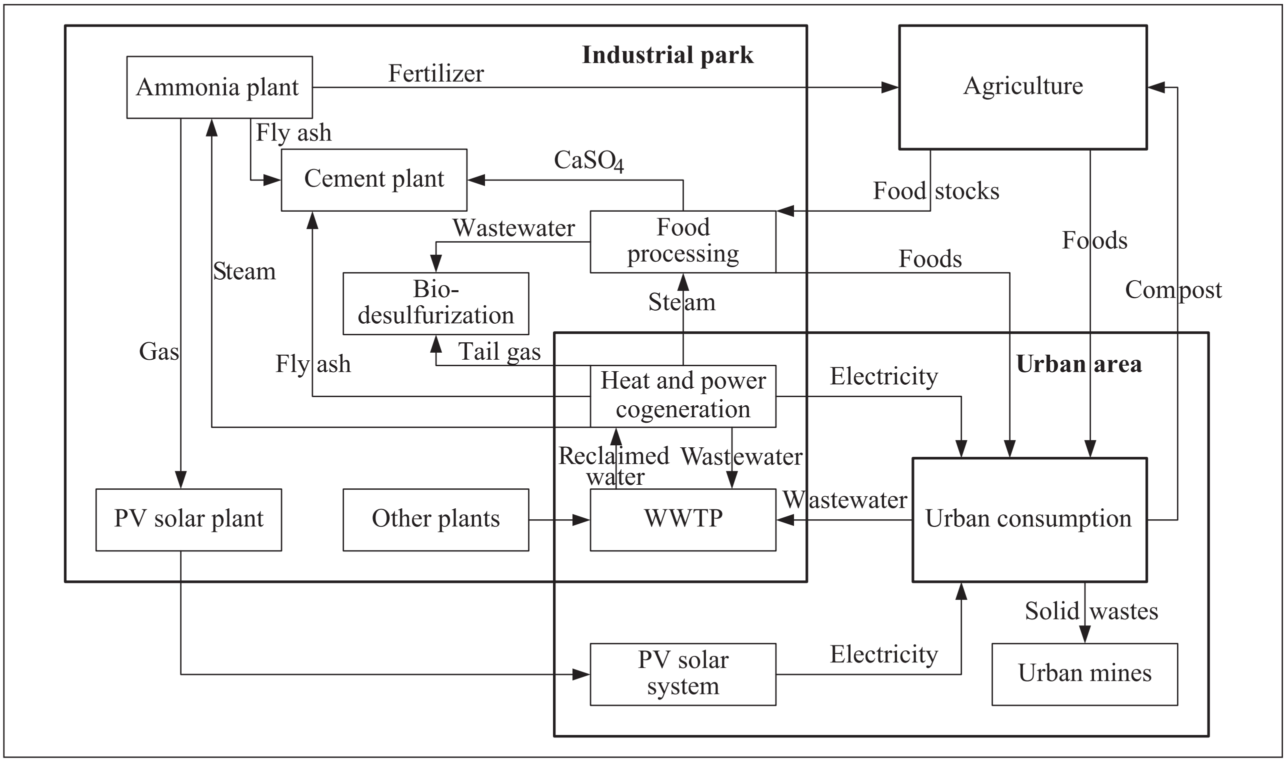

FIGURE 2 Interactions among industries and multiple urban-area infrastructure sectors—such as electricity, energy (steam), water supply, wastewater treatment plants (WWTP), and food systems—in the city of Yixing, China, show the potential for industrial symbiosis that can increase local resource availability. $CaSO_4$ = calcium sulfate; PV = photovoltaic. Source: Professor Shi Lei, Tsinghua University, China.

from engineering, urban planning, and public affairs, general concepts such as human capabilities, measures of water scarcity, and the linkage between infrastructures and human capability were not known to more than 80 percent of the students before the course. Afterward, they indicated that these concepts, in particular as put forth by Amartya Sen (2005), provided them with a broad view of sustainability and helped reconcile strong differences in ideology among participants. Likewise, specific principles and methods pertaining to development of environmental footprints or understanding of institutions were not initially known to more than 80 percent of the participants, but were reported among the skills and applications learned during the program (Ramaswami et al. 2012).

Interdisciplinary Systems Thinking and Teamwork Skills Linked with Fieldwork

Not all students are expected to achieve the highest skill levels in using all 40 concepts. We consider it more important for them to learn to work in teams by interpreting and transferring results across disciplines to address larger systems questions. Thus an urban planner need not be fully skilled in implementing air quality models, but should have the skill to understand the significance of model results. Such team-based interdisciplinary learning is promoted by using the schematic shown in Figure 3, which shows how learning about both social and infrastructure systems shapes sustainability outcomes.

Complementing the mapping of concepts in Figure 3 is the exposure of students to real-world field experiences in international cities. Such fieldwork involves tracking material-energy stocks, flows, and footprints of urban infrastructure, linking them with air quality and climate models, computing health effects based on populations exposed to diverse risks, and conducting surveys and interviews to assess how individuals, communities, firms, and policy actors respond to the various environmental and health outcomes. Figure 4 illustrates such integrated fieldwork in the context of understanding the burning and management of waste in Indian cities from a combined social, infrastructural, and environmental perspective.

Integrated field experiences are a powerful way to link disciplines and promote intercultural and inter-

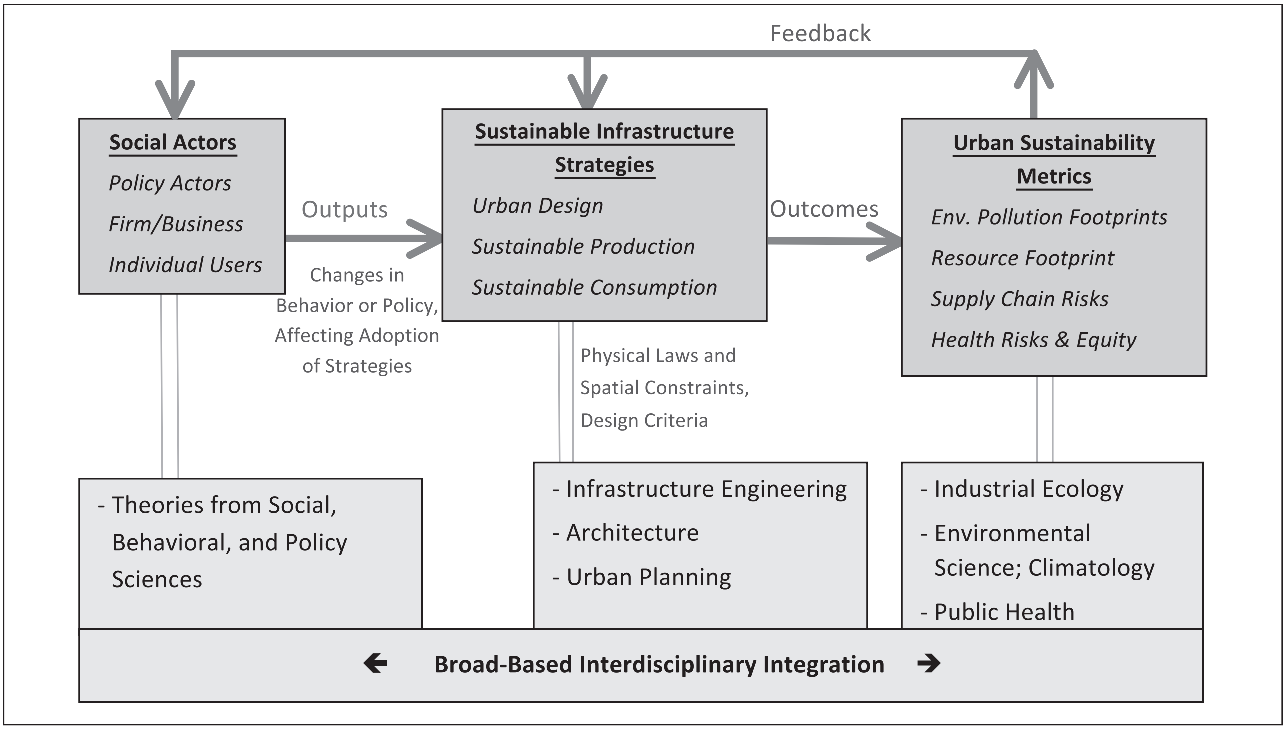

FIGURE 3 Schematic illustrating how integration across disciplines (bottom row of boxes) supports implementation of the social-ecological-infrastructural systems (SEIS) framework (top row of boxes). Adapted from Ramaswami et al. (2012).

disciplinary competence as well as awareness of ethical frameworks and responsibilities, as explained below.

Intercultural Skills

Intercultural learning requires an increased awareness of self and the ability to navigate differences with "the other" (the differences may be in gender, culture, profession—and, in this course, discipline).

Using Bennett's continuum for intercultural awareness (Figure 5; Bennett 2004, pp. 62–77) it is possible to assess various stages of development, from denial of other cultures (or disciplines) to polarization (assumption of the superiority of one culture or discipline over another) to minimization of differences (i.e., "we are all basically the same") to acceptance of differences and, at the highest level, the ability to negotiate and adapt to such differences.

For the 2013 summer school course in India, students' intercultural competence was assessed before and after, using the Intercultural Development Inventory (IDI; Hammer and Bennett 2009) to gauge their awareness of personal beliefs, understanding of the dynamics of interpersonal interactions across cultures, and development of their ability to reflect on and change their behaviors in real-world situations. Cultural and disciplinary differences and challenges were made explicit and discussed openly as part of the training program.

Wide variation was seen in cultural competence among individuals, reflecting the challenge as well as the reality of working across cultures and disciplines. To promote intercultural learning we used online resources collated by various universities,[4] books and videos presenting the history of India and China,[5] selected TED talks,[6] and, most importantly, opportunities for unstructured conversation and for "learning by doing" as students of different backgrounds worked together.

[4] For example, the On-Line Cultural Training Resource for Study Abroad, a resource established by the University of the Pacific School of International Studies and Tulane University's Payson Center for International Development and Technology Transfer with support from the Department of Education and the University of Southern California. Available at www2.pacific.edu/sis/culture/.

[5] For example, a BBC TV documentary series, "The Story of India," written and presented by historian Michael Wood, about the 10,000-year history of the Indian subcontinent in six episodes. Available at https://www.youtube.com/watch?v=cip4VmtCBWA.

[6] For example, a 2009 TED talk by Devdutt Pattanaik, "East vs. West: The myths that mystify," on myths of India and of the West. Available at www.ted.com/talks/devdutt_pattanaik.

IDI assessment results showed that most of the students transitioned from polarization toward minimization, the cusp between a monocultural and an intercultural mindset (Figure 5). Most students agreed afterward that "Learning how different disciplines and people from different backgrounds interact, both on a personal and professional level, was a good experience." One participant noted, "I learned so much from my peers. It was interesting to see the cultural differences seep into all conversations and discussions. I loved coming back and experiencing everything from a different perspective."

Knowledge of Ethics

Given large disparities in socioeconomic factors and infrastructure from one city to the next and from one country to the next, ethical questions are central to discussions of the development of sustainable infrastructure for sustainable cities. Discussions of ethics help bridge disciplines, professions, and cultures. Our curriculum incorporates ethics in five primary ways:

- *Distributional ethics* considers differences in benefits and burdens for different groups of people. What are the ethical frames for addressing social and environmental justice concerns associated with externalities

FIGURE 4 Integrated Fieldwork on Social, Infrastructural, and Environmental Factors in Cities. Some of the best opportunities for fieldwork arise spontaneously. Such was the case during the first summer school in India, when students spotted (and smelled) the burning of waste on streets. This practice affects air quality and respiratory health in many cities in India. Field work is exploring current and potential future waste infrastructure options, environmental/health impacts, and social actors, as illustrated in these photos. (A) Although banned in some cities, trash burning is widespread, serving not only to dispose of trash but also to provide heat in winter. Fieldwork is measuring the amount, composition, and frequency of waste-burns. (B) Air pollution monitors placed in the city assess the contribution of waste-burning to air pollution, and models estimate the health risks. (C-D) Interviews with social actors—households (left) and waste collectors (right)—assess their perceptions of health risks from waste-burning and views of alternative waste management strategies. (E) Studying areas with effective trash collection reveals what is working well both in the design of infrastructure and in social/behavioral practices.

of development, such as the higher risks that pollution and climate change may pose to children, the elderly, the poor, those living in particular locations, or even those in the future? Such frames include "polluter pays," Kantian duty ethics, and Rawlsian principles of protecting the weakest in society (Grubb 1998).

- In the context of *procedural ethics*, questions addressed include: Who has or should have standing to participate in discussions and decision making about issues that affect urban residents and workers? What are or should be the social processes? Do they ensure that all have a claim to justice? Scientific expertise is routinely part of societal decision making; how is it recognized and engaged in the process? Do procedures used in policy analysis, cost-benefit analysis, stakeholder engagement, or community-based research involve those most affected by an action? What does fairness require and what are the distributive consequences of one procedure rather than another? Questions of process and distribution also involve professional and research ethics.

- *Professional ethics* concerns the various disciplines and professions represented in Figure 3. Do they address questions of distribution or process? Intersections in statements of ethics among practitioners of engineering, urban planning, public affairs, social science and anthropology, and public health help students understand how each profession views its ethical responsibilities—and how an interdisciplinary team may define a new ethic to address the challenges of sustainable urban development (CSEP 2014).

- *Research ethics* is relevant to standards for researchers. Interdisciplinary work involves reconciling different professional codes and informal norms concerning matters such as publication credit, mentoring responsibilities, treatment of human and animal subjects, and data management. More recently, community-based participatory research has raised questions about research process, distribution of benefits, and community engagement in research design.[7]

[7] See, for example, the Northeast Ethics Education Partnership (NEEP), a joint project of Brown University and the State University of New York College of Environmental Science and Forestry (SUNY-ESF). Information available at www.brown.edu/research/research-ethics/neep.

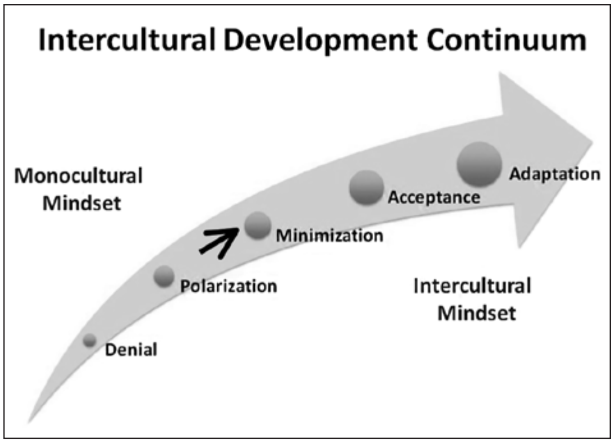

FIGURE 5 Intercultural Development Continuum (large arrow). The small black arrow shows the intercultural development of the 2013 cohort before and after the 6-week India summer program, measured using the Intercultural Development Inventory (IDI; Hammer 2014). The cohort transitioned from polarization to the cusp of minimization.

- *Cross-cultural ethics* applies to researchers from the same discipline who may have trained in different countries/locales with differing research codes and norms. Team members' views about what behaviors are acceptable in the field may be influenced by different cultural norms; attentiveness to these norms may be important to demonstrate respect for the host community, to complete the research successfully, and to develop long-term relationships based on mutual trust and respect. For example, it was helpful that US students grasped the need for cultural sensitivity in discussing the resource constraints of newly developing cities, given the large per capita allocation in developed economies.

Overall Evaluation of Various Learning Objectives

Individual learning objectives were assessed as shown for example, in Figure 5, for intercultural competence and, as reported in Ramaswami et al. (2012), for knowledge gained on sustainability concepts. In addition, students were queried about the effectiveness of the course in their own learning:

- 80 percent reported that the course was effective in promoting interdisciplinary systems integration and increasing their awareness of ethical dilemmas and responsibilities,

- 67 percent reported that the course promoted learning teamwork across disciplines, and

- 60 percent indicated the course was effective in promoting teamwork skills across cultures.

In their qualitative comments, the students described specific strengths and challenges associated with the course. Among the strengths, they reported that "we talked about culture & ethics as well as the subject matter relating to sustainable infrastructure, sustainable cities"; "The instructor spent time and effort on intercultural learning and interdisciplinary work. It was…a recurring theme in a very good way"; "International students, friendships, group work and small projects were the things that worked best"; "Meeting international faculty, specialists in their respective fields", "intercultural knowledge sharing" and the "SEIS framework—interdisciplinary and sustainability research that tied together"; "The opportunity to see parts of India and development challenges."

The challenges students experienced in India included "Lack of reliable communication with home"; "logistics around booking transport and accommodations"; "Too long and intensive"; "syllabus of 1 semester we had to finish in 1 month"; "difficult to reach every student."

The Way Forward

The summer school program on Sustainable Infrastructure and Sustainable Cities was implemented in India in 2013 and in China in 2014. Lessons learned from the first year informed the second year, including the addition of a preprogram in-person orientation and training for the participating students, improvements in travel logistics and planning, and reduction in the length of time spent abroad from about 7 weeks in India to 5 weeks in China.

The curriculum is intensive and requires much planning and about a 6-week commitment from students, but student feedback suggests that once logistical and time challenges are overcome, the impact can be high, increasing capacity for research and workforce development relevant for building sustainable cities in different countries. Students reported rich interdisciplinary, intercultural, field-based learning experiences about developing sustainable and healthy cities in an ethical manner.

Our experience demonstrates that focusing on the learning objectives described above in an international, interdisciplinary, blended lecture-fieldwork course can be an effective way to prepare leaders skilled at working in teams across disciplines and national borders to develop environmentally sustainable and healthy cities.

Acknowledgments

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Some industry trends are creating vulnerabilities that may produce systemic supply chain risks.

Systemic Supply Chain Risk

Yossi Sheffi and Barry C. Lynn

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Several significant natural and manmade disasters caused major supply chain disruptions during the past decade. But, although many observers lamented parts shortages and production delays, we argue that the global economy has not yet experienced a systemic supply chain disruption. However, the impacts of the recent disruptions may be harbingers of things to come and may require coordinated attention from industry bodies and governments.

Background and Definitions

The World Economic Forum (WEF) Global Agenda Council on Logistics and Supply Chain Systems focuses on systemic supply chain risks, and its 2012 and 2013 reports identified four types of events that may cause systemic disruptions to supply chain networks: environmental, geopolitical, economic, and technological (World Economic Forum 2012, 2013). The reports summarize current thinking about supply chain risks and their management, but do not address some fundamental issues of industry structure that may explain why a systemic supply chain risk may be growing.

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We define a *systemic supply chain risk* as the probability of a *systemic supply chain disruption*, an event that causes the widespread sustained shortage of a product or service with no alternatives or substitutes available. It is unclear that the world has experienced an occurrence that may qualify as such a disruption.

Clearly, natural disasters, wars, and political upheavals can create shortages in the affected areas, but we do not classify those as systemic supply chain disruptions unless they disrupt the ability to deliver goods and services outside the affected area. Similarly, entire industries can be affected in the short term by large-scale economic disruptions such as the "Great Recession" of 2008–2009 and the euro crisis, and in the long term supply chains will also be affected by certain trends such as global warming and population aging in the developed world. But while such risks may be systemic, they are not specifically supply chain risks.

Nonsystemic Supply Chain Disruptions

Given our definition, it is difficult to consider even the most frequently cited disruptions—such as those that followed the 2011 Japanese earthquake and tsunami, the 2011 Thailand floods, or the 2010 Eyjafjallajökull volcanic eruption—as systemic supply chain disruptions. None of these events caused widespread shortages, as we explain in the following specific accounts.

The Japanese triple disaster of earthquake, tsunami, and radioactive release caused a Japanese plant of Merck, which is the only producer of a pigment called Xirallic, to stop production, suspending the availability of certain metallic paint used by General Motors, Ford, Chrysler, BMW, and Volkswagen. While this affected several car companies and a few models, the fact that some customers were not able to obtain an Audi automobile with certain black shimmery hues or a Chrysler Jeep with the Bronze Star color can hardly qualify as a systemic disruption. Even the fact that France's PSA Peugeot Citroën had to slow production due to a shortage of air flow sensors made by Hitachi in Japan, or that GM idled its Shreveport truck manufacturing plant for a week (with 70 days' worth of finished product inventory on dealers' lots) cannot be described as systemic disruptions.[1] And while Japanese automobile manufacturers (mostly Toyota and Honda) had more significant production disruptions that lasted longer, Nissan was able to resume production quickly (Bunkley 2011). Furthermore, had the disruption persisted, other manufacturers were ready to fill the void and gain market share. At no time was the availability of automobiles in the world market, or in any region, in jeopardy. Alternatives were clearly available.

> *Supply chains will be affected by trends such as global warming and population aging, but such risks are not specific to supply chains.*

An individual company may, of course, face an existential threat when caught unprepared, as happened when a fire in March 2000 at a Philips Electronics fabrication plant in Albuquerque caused Ericsson, the Swedish manufacturer of mobile phones, to exit the handset business. The disruption did not change the fate of any other mobile phone makers, and in fact Nokia—a close competitor that relied on the same Philips plant—recovered quickly and ended up increasing its market share (Sheffi 2005).

Similarly, when the only US plant of Folgers Coffee, in New Orleans, was flooded in the aftermath of Hurricane Katrina, Procter & Gamble, the brand owner, was unable to manufacture and distribute the product for three weeks (Dash 2005). Yet there was no coffee shortage in the United States—other manufacturers filled the gap. In fact, the herculean efforts of Procter & Gamble to restart the plant were motivated by the reality that competitors were there to take up the slack.

Thus the robust capacity and multiple offerings of almost every product and service in today's world, and the increasing spread of engineering and manufacturing knowledge, are such that it is difficult to imagine a systemic shortage in which an entire industry is not able to operate its supply chains for a significant length of time.

The question, then, is, Do *any* systemic supply chain risks exist? The answer is "maybe."

[1] The plant was closed to divert certain parts that were expected to be in short supply to the manufacture of other, more profitable vehicles in other plants, but it turned out that this action was not necessary as the shortage never materialized.

Systemic Supply Chain Risks (1): Capital and Labor

Systemic supply chain disruptions are rooted in an unexpected change in an industry's ecosystem that affects either the demand or factors of production. When such disruptions are large, unexpected, or not mitigated ahead of time, governments may step in, particularly when the disruptions involve capital or labor.

Capital and Credit Risks

After the 9/11 terrorist attacks most US airlines experienced such a shortfall in demand that it threatened their existence. In response, Congress passed a massive aid package ($15 billion) that (at least temporarily) saved most of the domestic airlines from bankruptcy.

Governments also generally help individual leading companies if they are considered "too big to fail," as was the case during the 2009 financial crisis when the US government bailed out General Motors, with over $50 billion in loans and equity investment and another $14 billion in tax breaks.

> *A severe demand reduction can affect most industries but is not typically rooted in the supply chain function.*

Clearly a severe demand reduction can affect most industries and is not typically rooted in the supply chain function, as was illustrated by the threat of capital shortage in the form of a credit squeeze during the 2008–2009 Great Recession. Leading companies had to attend to their supply chain partners, which were not able to obtain credit and were in danger of bankruptcy. To ensure uninterrupted materials and part supplies, companies such as Procter & Gamble, Intel, and Ford helped their suppliers by shortening payment schedules, extending loans, and even taking equity positions in their suppliers.

Labor Risks

Labor is another factor of production that presents systemic business risk. Labor disruptions can pose systemic supply chain risks because labor is organized by industry.

In 2002 the US West Coast ports lockout, the result of a conflict between the International Longshoreman and Warehouse Union and the Pacific Maritime Association representing the ports' users, lasted 10 days. It halted the gargantuan flow of containers through 29 West Coast ports that are responsible for $320 billion in imports and exports each year. The ports typically process about 30 containers per minute, 24 hours a day, 7 days a week, so any disruption was bound to create costly chaos. Canadian and Mexican ports did not have the capacity to handle the huge amount of cargo that flows through US West Coast ports, and the post-Panamax container ships serving the Asia-US lanes were too big to pass through the Panama Canal to the East Coast. So the ships created a logjam all along the West Coast, placing a growing inventory of materials and products within sight but out of reach. As the cost of the lockout mounted, then-president George W. Bush intervened, invoking the Taft-Hartley Act of 1947 to force open the ports and push the parties back to the negotiating table (King et al. 2002).[2] The government intervened because this labor disruption caused a systemic risk to the US economy.

Vulnerability to labor disruptions may be limited in the United States owing to the government's legal recourse to prevent unions and companies from interfering for long with the flow of product. But this is not the case in many other countries; witness, for example, the power of labor unions in France, Greece, Italy, and Spain to shut down the economy.

Systemic Supply Chain Risks (2): New Vulnerabilities

Some industry trends are actually creating vulnerabilities in supply chains that may lead to systemic supply chain risks. The consequences of such trends usually are not well understood, take a long time to develop, and, even when pointed out, are beset by controversy and mired in debates between political ideologies.

Mergers and Geographic Concentration

One such trend is the merging of parts suppliers and their concentration in a few locations. These developments create points of vulnerability for entire industries and may contribute to systemic risks. Consider the tes-

[2] The United States may be less vulnerable to a similar disruption with the planned opening of the expanded Panama Canal in 2015.

timony of Ford CEO Alan Mulally before the Senate banking committee on November 18, 2008:

> If any one of the domestic companies should fail,…there is a strong chance that the entire industry would face severe disruption. Ours is in some significant ways an industry that is uniquely interdependent—particularly with respect to our supply base, with more than 90 percent commonality among our suppliers. Should one of the other domestic companies declare bankruptcy, the effect on Ford's production operations would be felt within days—if not hours. Suppliers could not get financing and would stop shipments to customers. Without parts for the just-in-time inventory system, Ford plants would not be able to produce vehicles.
>
> Our dealer networks also have substantial overlap. Approximately 400 of our dealers also have a GM or Chrysler franchise at their dealership. The failure of one of the companies would clearly have a great impact on our dealers with exposure to that company.
>
> In short, a collapse of one of our competitors here would have a ripple effect across all automakers, suppliers, and dealers—a loss of nearly three million jobs in the first year, according to an estimate by the Center for Automotive Research.

This would not have been the case when Ford was producing the Model A in the late 1920s and early 1930s: the company ran an integrated manufacturing complex at the River Rouge plant with raw materials flowing into the plant and finished cars coming out at the other end. The plant made every component the cars required. The complex also had its own power plant, steel mill, glass plant, casting plant, stamping plant, and much more. At that point, the collapse of a rival manufacturer or a tsunami in Japan would have had no effect on Ford.

In 2008, however, the industry looked very different. Many companies now focus on core competencies and outsource many manufacturing operations to both domestic and offshore suppliers. Thus General Motors and Ford spun off their Delphi and Visteon parts units, respectively, with the expectation that these large suppliers would serve all the automotive companies, and that is what happened. Visteon sells parts and systems to Ford, GM, VW, Tata Motors, and many others; few automotive suppliers match its breadth of product offerings. The unintended consequence of this was that in 2008 the CEO of Ford had to plead with Congress to save his competitors—the entire US automotive industry depended on a few large suppliers and could not afford their bankruptcy or liquidation (Lynn 2009).

Similar changes have taken place elsewhere. After a 1997 fire destroyed an Aisin plant making proportional valves for Toyota, all Toyota automotive manufacturing plants in Japan came to a standstill. The carmaker was able to recover relatively quickly with massive help from companies in the Toyota and Aisin keiretsu systems. Other car companies or suppliers in Japan were unaffected, and they assisted Toyota in its recovery efforts.

The entire US automotive industry depends on a few large suppliers and cannot afford their bankruptcy or liquidation.

In the past two decades, however, the Japanese keiretsu systems have adopted Western-style manufacturing architectures, in which original equipment manufacturers (OEMs) such as Toyota, Sony, and others procure parts and subassemblies from suppliers outside their keiretsu "ecosystems" (Lynn 2012).

In July 2007 automotive part maker Riken had to close a plant in Kashiwazaki city because of damage from an earthquake off the Japanese coast. Again, Toyota had to halt production in dozens of Japanese plants—but so did Nissan, Fuji Heavy Industries (makers of Subaru), and Honda: Riken supplied $1.50 piston rings to all of them. Again, the lost production was overcome relatively quickly but the event demonstrated the reliance of whole industries on certain key suppliers.

Emergence of Single, "Super" Suppliers

The outsourcing trend has allowed suppliers to grow by serving more customers, merging with each other during economic downturns (thus becoming "super suppliers"), and developing innovative parts and selling them to multiple OEMs.

Denso Corporation, for example, was spun off from Toyota in 1949 (although it remained in the carmaker's keiretsu for many years). Now it is a leading supplier to most automotive, trucking, and heavy equipment companies around the world, with revenues exceeding

$40 billion. Similarly, Bosch, the $65 billion German automotive supplier, furnishes most automotive OEMs with electronic and electric components, gasoline and diesel systems, car multimedia, control components, steering technology, and many other systems.

A strike, sabotage, financial problem, or cyberattack can shut down a supplier, affecting its entire operation even if it has multiple plants. The result may halt the operations of most OEMs in an industry, creating a systemic disruption.

The effect of a single supplier on multiple OEMs was illustrated in the April 2013 recall of more than 3 million vehicles worldwide by Toyota, Honda, Nissan, and Mazda. All were using improperly manufactured airbags made by Takata, a large Japanese automotive supplier that is the world's third largest automotive airbag manufacturer. And many US pet food manufacturers experienced a similar problem in April 2007, when they had to issue a massive recall after an FDA investigation of pet deaths traced the cause to a single Chinese supplier of tainted wheat gluten.

With the creation of "deep" multitiered supply chains it is impossible to monitor deep-tier suppliers or even know who they are.

Multitiered Supply Chains

Outsourcing has contributed to the creation of "deep" multitiered supply chains in which OEMs depend on tier 1 suppliers that, in turn, depend on tier 2 suppliers, and so on. It becomes impossible for OEMs to monitor deep-tier suppliers or even know who they are. Lower-tier (upstream) suppliers are typically reluctant to disclose their sources because the information is part of their intellectual property and a factor in their competitive advantage. In this way the suppliers also protect themselves from the likelihood that their customer (the OEM) might bypass them to buy directly from the lower-tier supplier.

Because suppliers may not know who their upstream deep-tier suppliers are, it can take a long time for the magnitude of a large disruption to become apparent. Three days after Japan's triple disaster of March 2011, General Motors' supply chain department identified 390 part numbers at risk. Procurement professionals looked for alternative suppliers for parts and materials, and engineers tried to find workaround solutions and qualify different parts and materials for use on the production lines. Despite the continuous work of the engineering, supply chain, and procurement divisions, the volume of part numbers at risk kept climbing, and reached a peak of 5,850 part numbers *11 weeks later*! This delayed visibility was due to the depth of the supply chain, the inability of OEMs to know the identity of deep-tier suppliers, and the lack of visibility into inventories throughout the chain.[3]

Geographic Concentration of Suppliers

Another type of vulnerability is rooted in the geographic concentration of suppliers. For example, almost a quarter of the world's integrated circuit (IC) design and fabrication capacity is concentrated between Taiwan's Hsinchu area and Taipei, which are only 40 miles apart. Taiwan is also home to almost 70 percent of the world's IC foundry capacity as well as most of the global capacity for IC packaging and testing. A Taiwanese disruption would affect most industries since most machinery now involves electronics. In fact, such a disruption took place in September 1999 when an earthquake disrupted semiconductor makers that account for 40 percent of the world's memory chip production. This occurred during a period of tight supplies, and the spot price of computer memory climbed fivefold all over the world, disrupting operations at many electronic suppliers and hampering the launch of certain Apple laptops (Lynn 2005).

The geographic concentration of suppliers in a single country may also expose supply chain operations to geopolitical risks. Interdependence theory holds that no nation will disrupt the flow of vital goods because that nation in turn depends on outside suppliers for other vital goods. Clearly, however, there are exceptions, and states have been known to withhold work in much the same way a labor union does to achieve some political or economic objective, as was the case when China decided in 2010 to embargo the shipment of rare earth

[3] It is a testament to the innovation, collaboration, and hard work of GM employees and their suppliers during the crisis that the Japan disaster did not affect GM production in any meaningful way.

metals to Japan during a dispute over territory and when Russia cut off Ukraine's gas supply (most recently in 2014) for political effect.

Industry Adaptations

In the aftermath of various global disasters and smaller disruptions, many companies have beefed up their crisis response teams and procedures, and started investing in more robust early warning and early mitigation processes. Even so, a fire and explosion at an Evonik plant in Germany on March 31, 2012, affected the supply of a crucial component for automakers around the world. The plant produces almost 50 percent of the global supply of CDT (cyclododecatriene), a chemical precursor used to produce nylon 12, which is the only material qualified for use in automobile fuel handling systems and brake lines. Emergency engineering changes and hurried qualifications of alternative sources by automotive OEMs prevented production shutdowns and a systemic supply chain disruption for the automobile industry.

Such "near misses," however, may be warning signs. For a variety of technical and commercial reasons, firms rely in major parts of their operations on single suppliers and often even on a single plant as formulations from different plants may vary enough to cause problems. Vulnerabilities often lie with suppliers that, at deep tiers of the supply chains, are not visible to the OEM. This is an Achilles' heel of many companies' business continuity efforts.

Companies may thus develop vulnerabilities without being aware of them. Leading manufacturers that recognize the issue work to diversify their sources, but commercial and technical factors limit the extent to which this can be done. And the mitigation of such vulnerabilities cannot be the purview of each company alone. While clearly OEMs and leading suppliers have the responsibility to protect their business—and they do—disruptions that affect entire industries are not always of major concern to them since their competitors are likely to be affected too, as was illustrated above by the experiences of Ford, Toyota, and other major manufacturers.

Consider also the response of AT&T after tropical storm Sandy, as reported in the *Wall Street Journal*[4]:

> John Donovan, AT&T's technology chief, said in an interview that all carriers' networks had been hit hard in Manhattan because the landline infrastructure that connects cell phone transmitters to the wired telecom network had been damaged in the storm. He said AT&T conducted extensive drive testing in Manhattan this week and found negligible difference in performance of the wireless network.

This quote illustrates the fact that part of AT&T's concern was its performance vis-à-vis competitors.

Firms may rely on a single supplier or even a single plant as formulations from different plants may vary enough to cause problems.

Individual companies may appear to show a lack of concern about systemic risks, and from their point of view this may be a rational position. One never knows how much should be invested in disaster recovery and resilience, since it involves preparations for low-probability, high-impact events, so one metric for "enough" investment in preparedness is the "industry standard"—what competitors and others in the industry are doing. The development of guidelines for minimal risk assessment and preparedness may be an appropriate task for an industry body or a regulator, but companies can often gain a competitive advantage by going beyond the minimum and developing their own resilience systems.

Identifying and Mitigating Systemic Risks

The roots of systemic supply chain risks can be classified as follows:

- Geographic concentration: the clustering of many suppliers in a single region
- Supplier integration: the emergence of "super suppliers" who can put an entire industry at risk if they fail
- Deep-tiering: the reliance of many manufacturers in a given industry on a single supplier or a small set of clustered suppliers buried deep in the supply chain

Geographic concentration of tier 1 and tier 2 suppliers is something that many leading companies monitor already. They rate their vulnerability to various suppliers

[4] Anton Troianovski and Sarah Portlock, "Outage Exposes Carriers' Backup Plans," *Wall Street Journal*, November 2, 2012.

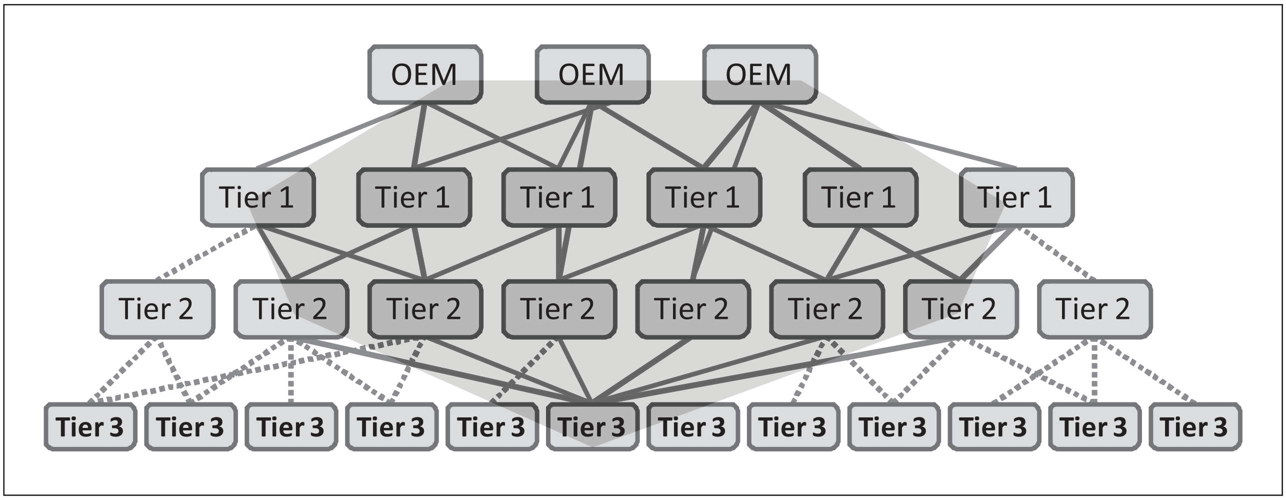

FIGURE 1 An industry supply chain schema with a "diamond" vulnerability.

and, based on assessment of the risk, may qualify new suppliers or even dual-source at times. But some mitigation efforts are too expensive and therefore are not pursued.

As shown in Figure 1, a diamond shape illustrates the dependence of multiple OEMs in the supply chain on a single deep-tier supplier. This dependence is highlighted by the solid lines representing parts flow; the dashed lines represent parts flows that depend on other tier 3 suppliers. The solid lines reveal a diamond structure (shaded in the background) as opposed to a tree structure, which characterizes typical supply chains based on the bill of material. If the tier 3 supplier at the sharp end of the diamond is producing a large fraction of what the industry consumes, without ready alternatives, a systemic risk looms.

This diagram could similarly depict dependence on suppliers in a single geographic location or national control of supplies critical to an industry.

Concluding Thoughts

Governments have the tools to intervene in the case of certain significant disruptions, regardless of their nature. They use their resources after floods, hurricanes, and earthquakes to help affected communities rebuild, and are also involved in predisaster mitigation efforts, collaborating internationally in antiterrorism activities and in efforts to develop standards and processes for mitigating other global risks. They even take coordinated actions, such as the joint navy operations to fight piracy off the coast of Somalia.

Another role for the government may be to watch for the danger associated with supplier integration. The US Justice Department, Federal Trade Commission, and European Directorate General for Competition scrutinize possible mergers for their effect on consumers, mainly to prevent monopolies. But these agencies are not equipped to review mergers in terms of their effect on systemic supply chain risk—to assess whether, for example, certain suppliers may become "too big to fail." Such a review might entail preventing certain suppliers from merging or extracting certain merger conditions, such as a requirement to diversify parts of the merged business or to operate multiple plants of certain types.

Overcoming companies' reluctance to invest in strong mitigation efforts may require an audit, whether by financial auditors or specialty firms, to point out systemic supply chain vulnerabilities and, ideally, bring market discipline to mitigation efforts. Alternatively, discovery of unknown risks may be better accomplished by either extending the purview of existing industry bodies (e.g., the Automotive Industry Action Group, the Electronic Industry Citizenship Coalition) or creating new groups for this purpose.

The time may have come—before a systemic supply chain disruption actually takes place—to develop these capabilities.

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The rise in global temperature, current emission levels, and minimal international action to mitigate climate change are rapidly reducing the time available to meaningfully address the problem.

Why Climate Action Is Urgent

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Present climate change is a manmade problem of global scale and consequences. Climate knows no borders and distinguishes no countries: all nations are susceptible to the impacts of climate change.

Overview

Carbon dioxide (CO_2) is the main greenhouse gas (GHG) in the atmosphere responsible for long-term global warming, and scientific evidence

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indicates that the current CO_2 concentration is probably the highest in the last 15 million years (World Bank 2012)—more than 391 parts per million (ppm), compared to the preindustrial level of 278 ppm. CO_2 emissions grew 1.1 percent per year from 1990 to 1999 but since 2000 they have been growing by more than 3 percent per year (Gowdy 2010). The National Oceanic and Atmospheric Administration (NOAA) reported a reading of CO_2 at Mauna Loa of 400.03 ppm on May 9, 2013, crossing for the first time the 400 ppm mark.[1]

Global warming due to past anthropogenic CO_2 emissions is irreversible for at least 1,000 years, and current and future CO_2 emissions will result in additional warming (Matthews and Solomon 2013). The international community has set the goal of stabilizing global warming at no more than 2°C above preindustrial levels by 2100, while the Small Island Developing States (SIDS; www.sidsnet.org) have set it at 1.5°C. But given current emission levels and minimal international action to mitigate climate change, "there is roughly a 20 percent likelihood of exceeding 4°C by 2100" (World Bank 2012, p. 1).

It is still possible, however, to keep global warming within tolerable limits through the use of appropriate technologies to replace fossil fuel consumption with other energy sources and the application of international political will to change course and control climate change. Any delay of such action will commit the planet to higher and higher temperatures that will become irreversible in the foreseeable future. The likely consequences will be dire.

Some Consequences

If current CO_2 emissions are not abated and a 4°C warming above preindustrial levels is reached by 2100, the likely stresses on society will be severe. Warming at higher latitudes will be greater than in the tropics, but the impacts will be greater in the latter, thus disproportionately affecting the poorer regions of the planet (World Bank 2012). Agriculture and ecosystems in the tropics will be stressed not only by higher temperatures but also by more intense cyclones, and sea level rise may be up to 20 percent greater than average. In the United States a recent study predicts that, if emissions continue unabated, increased flooding is likely and snowfall on the mountains of southern California may be reduced by 30–40 percent compared to snowfall at the end of the 20th century (Sun et al. 2013).

Past climate records could provide an idea of what might happen with a 4°C warming. The sea level was 120m lower during the last ice age when average temperatures were 4–7°C lower than they are now, and 25–35m higher when temperatures were 2–3°C higher, 3 million years ago during the Pliocene Epoch (Allison et al. 2009).

Delays in action will commit the planet to higher and higher temperatures that will become irreversible in the foreseeable future.

National security will also be at risk from climate change as food scarcity and famine, epidemics and pandemics pose international security threats. A recent report of the National Academy of Sciences (Steinbruner et al. 2012) links climate change to possible societal breakdowns and conflicts due to health problems and food and water scarcity in certain regions. Migration within and between countries may increase dramatically—especially associated with megacities in the delta regions of Asia and Africa under the stress of sea level rise—with possible violent consequences. Water resources will be stressed severely as some dry areas, such as the Middle East and the Sahel Region, become drier. There is no substitute for clean water and its scarcity can be a source of conflict.

Economic Aspects

It has been suggested that the reluctance of the United States and China to sign the Kyoto Protocol in support of controlling GHG emissions (although they signed the Montreal Protocol, which phased out the use of ozone-depleting substances) stems partly from economic considerations (Sunstein 2006). Both countries were projected to incur higher costs than benefits by signing

[1] "Carbon Dioxide at NOAA's Mauna Loa Observatory reaches new milestone: Tops 400 ppm," May 10, 2013. Available at http://research.noaa.gov/News/NewsArchive/LatestNews/TabId/684/ArtMID/1768/ArticleID/10061/Carbon-Dioxide-at-NOAA%E2%80%99s-Mauna-Loa-Observatory-reaches-new-milestone-Tops-400-ppm.aspx.

the Kyoto Protocol, whereas the opposite was perceived to be true for the Montreal Protocol. European countries, on the other hand, signed the Kyoto Protocol for different reasons. Germany, for example, experienced lower GHG emissions after reunification, thanks to East Germany's bad economy, whereas the United Kingdom reduced its emissions by subsidizing natural gas.[2]

Natural catastrophes in 2011 caused $400 billion in overall losses worldwide.

Uncertainty and Variability in Economic Assumptions

Economic valuations of future climate gains and losses present many difficulties partly because of tremendous uncertainties. Modelers often resort to simplistic assumptions to handle the complexities of the problem, with the result that valuations exhibit considerable variability and sometimes questionable conclusions. One such valuation found that a 2.5°C warming would benefit Russia to the tune of 0.65 percent of its GDP (Baird and Morrison 2005), but the country's 2010 heat wave cost 55,000 lives, 25 percent of crop production, and 1 million hectares of land burned by wildfires—in economic terms, a loss of about $15 billion or 1 percent of GDP (World Bank 2012). Such extreme events would be very rare in the absence of climate change but are likely to happen more frequently as climate warms.

Two commonly cited economic models of the costs of climate change mitigation were developed by Nordhaus (1994) and Stern (2007). The former uses a discount rate of about 3 percent and suggests moderate mitigation action while the latter uses 1.5 percent and suggests more aggressive measures. A higher discount rate values the climate impact on future generations less. More importantly, the choice of discount rates reflects values rather than objective scientific method.

One estimate of damages associated with a 2.5°C warming predicts losses of $113 billion per year in the United States alone (in 1990 US dollars; Hanemann 2010). In contrast, another estimate by Nordhaus (1994) is $28 billion. And according to Stern, if no mitigation action is taken, at least 5 percent of global GDP annually will be lost in costs and risks associated with climate change. Such a number should have shocked nations into action, but it hasn't.

In addition to differing discount rates and projected economic losses, most economic models use average temperatures with no regard for variability. But a temperature rise of 2°C globally implies a 2.3°C winter rise and a 4.6°C summer rise in California (World Bank 2012), and in the state's agricultural Central Valley the rise will be 5°C, which would almost certainly have negative effects on farming and food production.

The point is that climate change valuations vary according to assumptions. However, reality suggests that less conservative economic estimates might represent the future more reliably. According to Munich Re, a leading global reinsurer, natural catastrophes in 2011 caused $400 billion in overall losses worldwide and $160 billion in 2012.[3] In January 2013 Australia suffered a prolonged heat wave that forced the country's Bureau of Meteorology to add two new colors, deep purple and pink, to its weather forecasting chart to cover record temperatures of 47.8°C. The heat wave caused a number of fires to spread across the country. These conditions in Queensland and northern New South Wales were ended in the last week of January by severe flooding caused by tropical cyclone Oswald. The economic cost of the heat waves and wildfires (as well as floods) has yet to be estimated.

Finally, economic studies examine only a limited spectrum of climate change consequences. There are no comprehensive assessments of the economic and ecological consequences of a possible collapse of coral reefs, loss of marine life, or loss of human settlements to rising seas due to climate change (World Bank 2012).

Neoclassical Economic Models and Human Behavior

Most economic discussions in the context of climate change rely on the basic tenets of the neoclassical model, which have been criticized on various grounds. For

[2] Other factors, not discussed in this article, play an important role in the decision to join an international climate agreement: pressure by powerful private agents such as oil companies, public opinion (which hinges on properly informing citizens), and perceived national interests.

[3] ABC News, "Reinsurer estimates 2012's disasters cost $160b," January 4, 2013. Available at www.abc.net.au/news/2013-01-04/reinsurer-estimates-2012s-disasters-cost-160b/4452288.

example, Gowdy (2010) offers the following criticism of Nordhaus's dynamic integrated climate-economy (DICE) model (Nordhaus 1994):

- The only value assigned to climate is economic.
- There is no regard for humans as social and biological creatures.
- Human well-being is measured by income and mitigation policies are justified only on the grounds of income increase.
- Future income is discounted subjectively.
- The model is static, unlike economic reality, which is highly dynamic.
- Consumers and producers are assumed to be autonomous and thus unaffected by other producers and consumers.
- There is always a substitute for goods. This proposition violates common sense that dictates that there are no substitutes, for example, for drinking water, lost species, or a stable climate.

Neoclassical economic models assume that humans are rational actors making purely rational decisions, but evidence from the social sciences points in the opposite direction (Gowdy 2008; Kahneman and Tversky 1979). A number of experiments have demonstrated that people have a sense of fairness and social responsibility that goes beyond maximization of their own monetary gain; for example, blood donations decline when payment to blood donors is introduced (Buyx 2009).

It is also a well known fact of behavioral economics that people usually exhibit an aversion to loss (Kahneman and Tversky 1979) and that their willingness to pay for a gain is greater than their willingness to accept a loss. So it is reasonable to suppose that, when properly informed about climate change, people would be willing to pay to avert an imminent loss rather than continue the present course that leads with high probability to greater loss.

Climate change is already affecting humans and the environment, and the scale of phenomena experienced today will likely worsen in the near future. In this context human needs extend well beyond economics, and models that view climate through a narrow economic lens miss most of the picture of humanity and life. Monetary values cannot be assigned to the inability to be active outdoors because of excessive heat, or to the suffering associated with disease, lack of water, hunger, or the loss of a homeland sunk in rising seas.

Social Aspects: Importance of Public Understanding

Report of a Survey

We recently conducted a survey in Greece about climate change. We devised two questionnaires accompanied by a brief introduction on the effects of climate change; the second survey also presented information showing that renewables can satisfy global human energy demand of 125 kWh per day per capita, which is the average British and European consumption level (McKay 2009, p. 104) and guarantees a comfortable lifestyle. In our sample of 930 respondents, 84 percent were students of higher education.

> *It is impossible to assign monetary values to suffering from disease, lack of water, hunger, or the loss of a homeland sunk in rising seas.*

The first question was "Do you agree with the investments of foreign governments in new fossil fuel sources?" The extra information about renewables had no statistical effect on the responses of the second survey: 56 percent of all the respondents believed that it is important for foreign governments to invest in fossil fuels. The number jumped to 75 percent in the second question when this investment concerns Greece, presumably because of claims that oil sales will pull the country out of its present economic crisis. About 64 percent believed that Greece will benefit from such investment, but when asked if the country's children would benefit, the positive responses dropped to 53 percent. When respondents were asked in the third question whether they would make a one-time donation of €500 to a "good effort" to mitigate climate change, 43 percent said yes.

The fourth and last question was "Would you agree to pay a 3 percent annual income tax to mitigate climate change if the probability of failure (you lose your money) were 20 percent, 50 percent, 80 percent, or would you say no?" This question was also phrased slightly differently by referring to the probability of *success* at 20 percent, 50 percent, or 80 percent. Interestingly, when loss was mentioned 66 percent agreed to the tax, whereas when success was mentioned the positive responses went up to 82 percent, although the meaning of the two questions was identical. Loss aversion may be responsible for this discrepancy. Also, to most people a one-time contribution of €500 appears to be greater than an annual tax of 3 percent, although the opposite is true in the majority of cases over the long run.

Realistic economic assessments show that climate mitigation will pay off by opening investment opportunities in alternative energy conservation and generation technologies.

Findings

The importance of public opinion cannot be overemphasized. Our survey exposed a few major points. First, the public is generally not well informed about climate change. Second, people often make decisions based on emotion without going into deeper details, as in the case of the monetary contributions. Third, immediate dangers and concerns (e.g., Greece's economic crisis) eclipse future possibilities of enormous disasters. Although loss aversion is a strong force in decision making, the future is perceived as something too remote to matter much. From an evolutionary point of view, it seems that humans are not well equipped to grasp future dangers. Finally, people's decisions and opinions depend heavily on the way information is presented to them.

The success of a campaign to prevent catastrophic climate change depends to a large degree on how well the public is informed. New and fairly complex information takes many years to trickle down. An energetic campaign would have to take into account that people's perception of loss or gain depends on how information is framed and not merely on the facts of a message.

What to Do

All scientific evidence indicates that climate change is already occurring, with detrimental effects for humanity and the global ecosystem. Political action by all nations is therefore urgent. Further delay will render the 2°C goal technically impossible. Carbon trapped in Earth's crust must stop being released into the atmosphere. The burning of fossil fuel is unsustainable from the point of view of not just availability but, more importantly, environmental damage.

Energy Technology

Is there an alternative? MacKay (2009) makes a compelling case that there is. A combination of renewable energy production, adoption of new transportation technologies such as electric cars, energy-saving practices, new home designs, proper energy regulation and pricing, and installation of large-scale solar systems in deserts, among others, have the potential to guarantee a high standard of living while mitigating climate change and preserving the planet. Given present technological capabilities, all of these measures can safely provide for every citizen on earth a daily energy amount of 125 kWh, which is the current average daily per capita energy consumption in Britain and the European Union. In other words, phasing out fossil fuel burning without compromising standard of living is technically feasible.

International Leadership

The missing ingredient is political will and action. It seems difficult to achieve the 2°C goal given the current state of emissions and the reluctance of major emitters to take immediate action. If the United States and China, the two major GHG emitters, engage in serious international climate discussions, most other nations will follow suit. Realistic economic assessments show that climate mitigation will pay off not only by reducing damages but also by opening new investment opportunities in alternative energy conservation and generation technologies. US leadership and participation in international discussions and agreements will add influence that the Kyoto Protocol lacked.

Furthermore, in times of economic stagnation nations place climate change mitigation at the bottom of their priorities. However, a recent study showed that when economic growth is lower, the social cost of CO_2 increases because climate impacts have more severe effects on weaker economies (Hope and Hope 2013). Thus, contrary to intuition, it "pays more" to mitigate climate

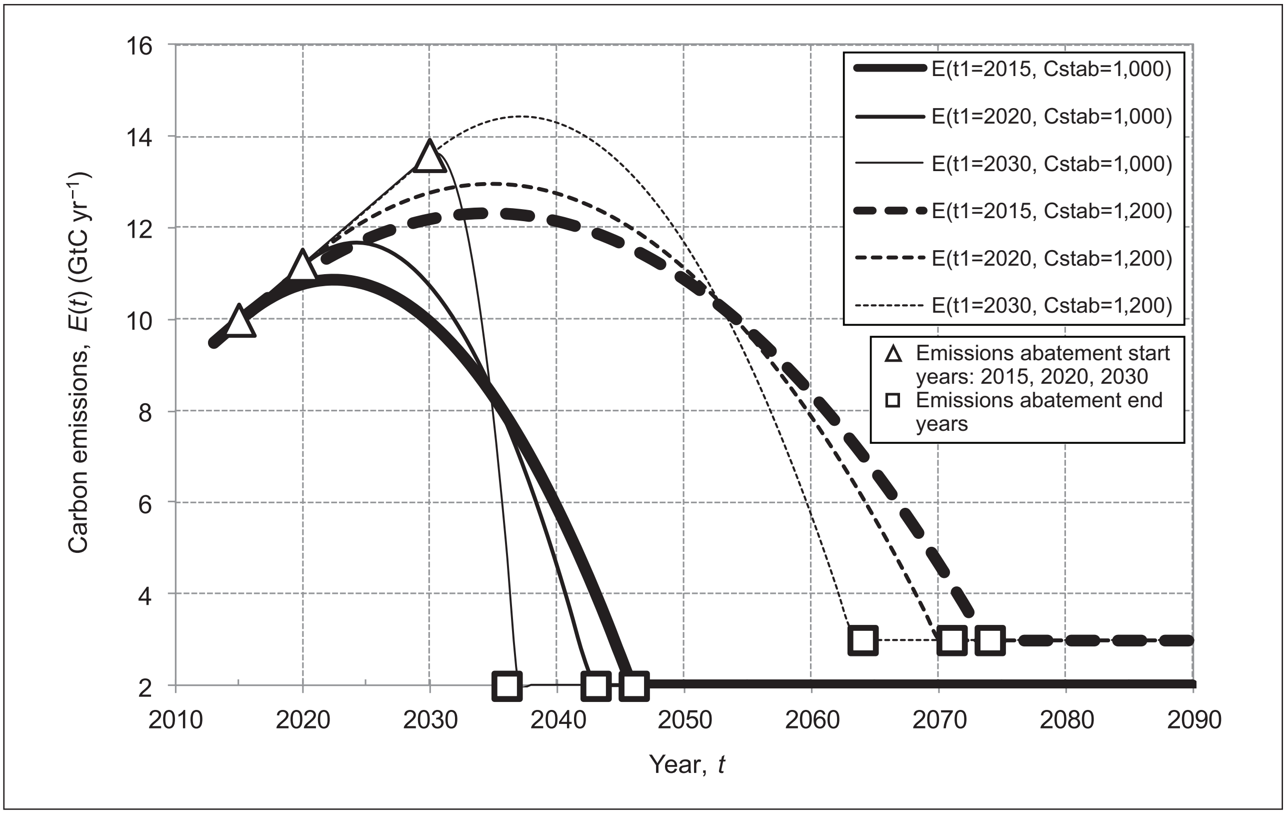

FIGURE 1 Annual emissions of parabolic policies ensuring 1,000 and 1,200 gigatons of carbon (GtC) stabilization levels and corresponding emissions of 2 and 3 GtC yr^{-1}, 2015–2090. (E(t) = carbon emissions in year *t*, C_{stab} = stable level of concentration.)

change when the economy grows less. So economic hardship is a poor excuse for climate mitigation avoidance.

A first step in the direction of climate change mitigation would be the abandonment of long-term planning in fossil fuel technologies. Unfortunately, many nations—most notably the United States, Canada, Australia, Israel, Greece, and Cyprus—are frantically searching for new oil and natural gas, and in some cases disputes over fossil fuel rights awaken old animosities (e.g., between Turkey, Cyprus, and Greece). Energy investments in fossil fuels carry with them the baggage of irreversible further warming. Building new coal-fired power plants, for example, commits nations to the emission of enormous quantities of CO_2 for at least 50 years. Yet in March 2013 a €1.4 billion project was signed to build a new 660 MW lignite-fired power plant in northern Greece—ironically, with funds from Germany, a country that aspires to supply 40 percent of its energy needs with renewable sources in the coming decade.

Policy Scenarios

To gauge the urgency of climate change mitigation, we simulated the impacts of a number of policies over time (as explained in our appendix and illustrated in Figure 1) using a dynamic emissions model proposed by Socolow and Lam (2007). We examined three scenarios of climate action, starting in 2015, 2020, and 2030, using the latest emissions data in conjunction with parabolic policies, which permit smooth growth of emissions at the time of action and then parabolic reduction until a given level of carbon in the atmosphere is reached.

The most optimistic scenario starts in 2015, reaching in 2046 the goal of stabilization at 1,000 gigatons of carbon (GtC), which corresponds to a 2°C warming, and steady-state emissions of 2 GtC/year, while 1,200 GtC were reached in 2074 with steady-state emissions of 3 GtC/year thereafter (current annual emissions are about 9.5 GtC; World Bank 2012). A more realistic scenario of action starting in 2020 stabilized the climate at the two levels in 2043 and 2070 correspondingly. Finally, action in 2030 resulted in the 2°C warming in just 7 years.

Clearly, any further delay of concerted political action will bring 2°C warming closer and likely create conditions for higher irreversible warming.

Conclusion

Time is of the essence. Further postponement of significant action to mitigate climate change and its impacts reduces the possibility of achieving the goal of 2ºC. This is a multifaceted problem of global dimensions that requires multilateral action.

Adequate information is available about climate change and how to control it technologically. We show here that mitigation efforts should begin as early as 2015. Climate change is already a significant threat, but response has to be collective. We hope leaders will see it as such—or that the public will nudge them in this direction.

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Appendix

The total carbon content (in GtC) in the atmosphere in year t is denoted $C(t)$ and the carbon emissions (in GtC yr^{-1}) in that year $E(t)$. Computer simulations of detailed carbon cycle dynamics have demonstrated that, once the carbon content reaches any designated value C_{stab}, a constant emissions level $E(t) = E_{stab}$ thereafter stabilizes $C(t)$ to this value. From this observation Socolow and Lam (2007) proposed the following approximation of atmospheric carbon dynamics:

$$\frac{dC(t)}{dt} = \lambda\left[E(t) - E_{stab}\right] \tag{1}$$

Good parameter approximations of the above model are

$$E_{stab} = \frac{C_{stab} - 600}{200}, \ \lambda = 0.58\frac{E(t_0)}{E(t_0) - E_{stab}}$$

for any initial year t_0 for which $C(t_0) < C_{stab}$ and $E(t_0) > E_{stab}$.

The aim here is to examine how fast the atmospheric carbon accumulation reaches a critical value C_{stab} under various emissions policies and to determine the corresponding paths, $\{E(t), t \geq t_0\}$. Out of all possible stabilizing policies, the following subclass is examined. There is an initial period of inactivity, $[t_0, t_1)$, during which annual carbon emissions increase at rate R_0 (GtC yr^{-1}) following a business-as-usual (BAU) policy. At time

t_1 an emissions mitigation policy is implemented and reduces the rate of emissions. Finally, at some time t_2 the total carbon accumulation reaches the C_{stab} level and is stabilized by keeping emissions fixed at E_{stab}, according to Eq. (1).

A simple family of emissions paths that exhibit such a behavior is the class of parabolic policies:

$$E(t) = \begin{cases} E(t_0)+R_0(t-t_0), & t_0 \le t < t_1 \quad \text{(nonabatement period)} \\ at^2+bt+c, & t_1 \le t < t_2 \quad \text{(abatement period)} \\ E_{stab}, & t_2 \le t \quad \text{(stable period)} \end{cases}$$

The initial year is $t_0 = 2013$.[4] Initially, total carbon accumulation and emissions to the atmosphere are respectively $C(t_0) = 840$ GtC and $E(t_0) = 9.5$ GtC yr^{-1}. Emissions increase at a constant rate $R_0 = 0.24$ GtC yr^{-2} during the BAU period $[t_0, t_1)$. Parameters t_2, a, b, and c are chosen so that the concentration target is achieved and maintained by an emissions trajectory $E(t)$, which is continuous for all t and smooth at t_1. The corresponding constraints are:

integration of Eq. (1) to t_2 equals $C(t_2) = C_{stab}$
continuity of emissions at t_1: $E(t_0)+(t_1-t_0)R_0 = at_1^2+bt_1+c$
continuity of emissions at t_2: $at_2^2 + bt_2 + c = E_{stab}$
continuity of emissions growth rate at t_1: $R_0 = 2at_1 + b$

Three scenarios are examined for the start of the mitigation period (t_1 = 2015, 2020, 2030) and two target concentrations (C_{stab} = 1,000 or 1,200 GtC). Figure 1 shows that the later the mitigation policy starts, the larger the corresponding cutbacks and the sooner the carbon concentration reaches the critical level. Thus if mitigation efforts are delayed until 2030 the 2°C stabilization temperature is reached in just 7 years.

[4] To avoid loss of significance in the floating-point calculations due to the use of large arguments in the quadratic function, our computer model offsets all times by 2013 setting $t_0 = 0$.

Some 35,000 fuel cells were shipped worldwide in 2013 and carmakers are announcing plans for commercial fuel cell vehicles. The industry is poised to make headway.

Hydrogen and Fuel Cells

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Sunita Satyapal

Hydrogen and fuel cell technologies are part of the US Department of Energy's (DOE) balanced portfolio of research and development activities. Significant progress has enabled market entry, with an estimated 35,000 fuel cells shipped worldwide just last year. Fuel cells are now being used for backup power, primary power, and early market applications such as forklifts and even cell phone chargers. Fuel cell cars are starting to be leased and automakers have announced plans for commercial sales as early as 2015. Given all the recent advances, this article provides an overview of the advantages and disadvantages of hydrogen and fuel cells, the current status, and a summary of progress and remaining challenges.

Advantages

Fuel cells can use diverse fuels and generate electricity directly through an electrochemical reaction rather than through combustion, which can waste more than two-thirds of the fuel energy content as heat. Figure 1 lists different types of fuel cells, primarily distinguished by their electrolytes (e.g., polymer electrolyte membranes or solid oxide ion conducting electrolytes), and diverse applications ranging from portable power at a scale of just a few watts to large, stationary, multimegawatt central power generation.

For automotive applications, the fuel cell of choice is the proton-exchange (also called polymer-electrolyte) membrane (PEM) fuel cell, which operates

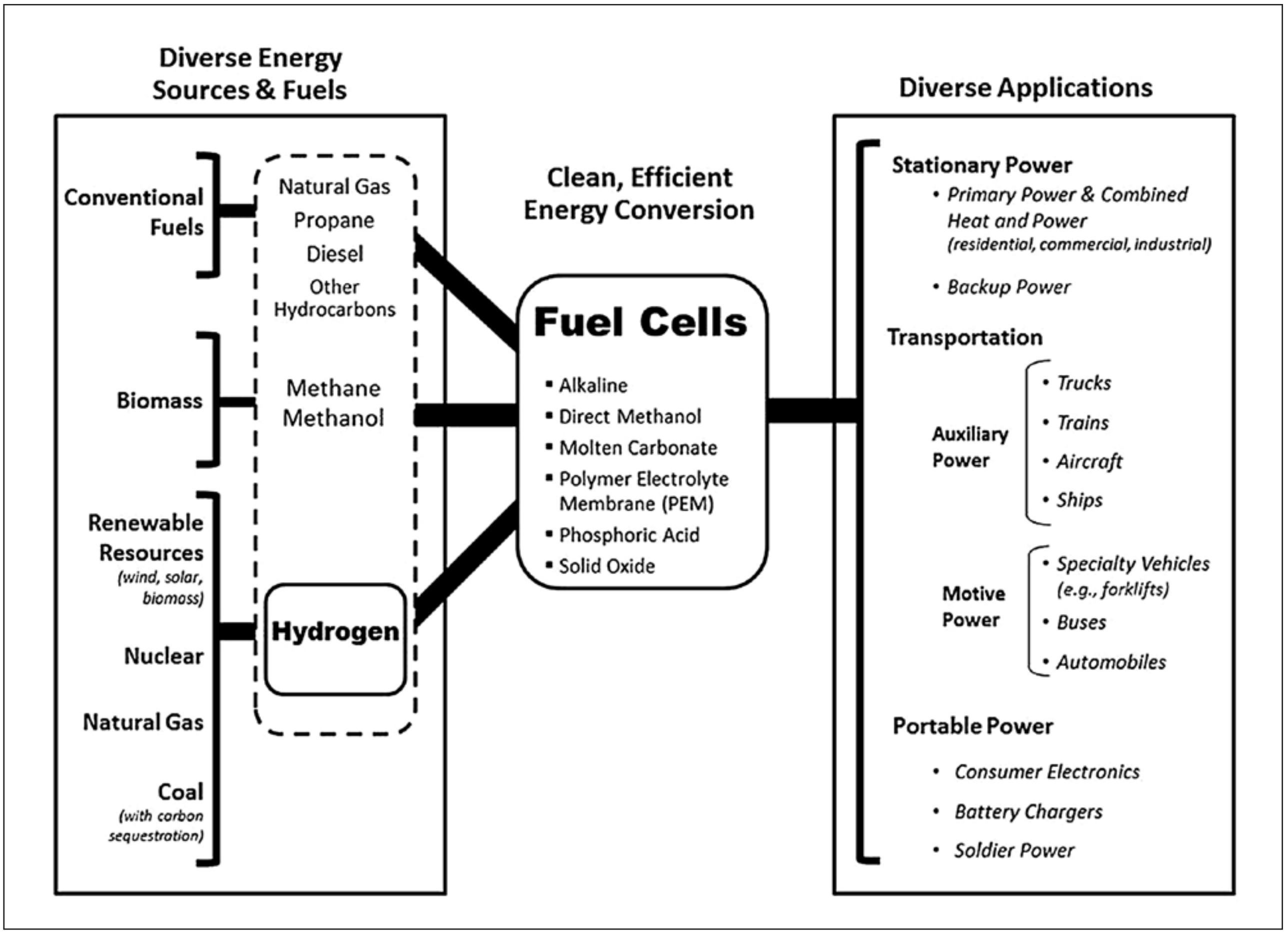

FIGURE 1 Fuel cells: fuels and applications. On the left side of the figure are fuels that may be used in fuel cells to generate electricity, and on the right applications in which fuel cells may be used. The center box shows different types of fuel cells based on their electrochemistry.

at around 80°C and has rapid startup and response times and high power densities. Key advantages of hydrogen-fuelled transportation applications are that hydrogen can be produced from diverse domestic resources, and the only emissions from the point of use are water and a small amount of heat. Because there is no combustion involved, fuel cells are highly efficient. In contrast, just over 20 percent of fuel energy content is actually used to move gasoline-powered automobiles, taking into account losses such as heat, air drag, rolling friction, and brake losses (Chu and Majumdar 2012).

Fuel cell electric vehicles (FCEVs) are one approach among a number of others (e.g., hybrid vehicles, higher-efficiency combustion engines, electric vehicles, and plug-in hybrids) being pursued to improve the efficiency of light-duty vehicles. Global automakers have spent billions of dollars over more than a decade to bring FCEVs to the market and are just starting to lease commercial vehicles and announce plans for sales in 2015–2017.

In addition to the efficiency improvement—by about a factor of two—of fuel cells over conventional gasoline internal combustion engines, vehicle performance can be on par or better. The driving range of FCEVs can exceed 250 miles on a single tank, with refueling times of just a few minutes, as demonstrated with more than 180 FCEVs and 3.5 million miles of driving (Wipke et al. 2012). Some models were capable of up to 430 miles without needing to refuel, as shown by independent on-road validation (Wipke et al. 2009), demonstrating that range is no longer an issue.

Moreover, since full torque is available from a standing start, FCEVs do not require multiple shifting of gears to get up to speed, and acceleration is smooth and quiet without the noise associated with a continuously variable transmission. Automakers such as General Motors

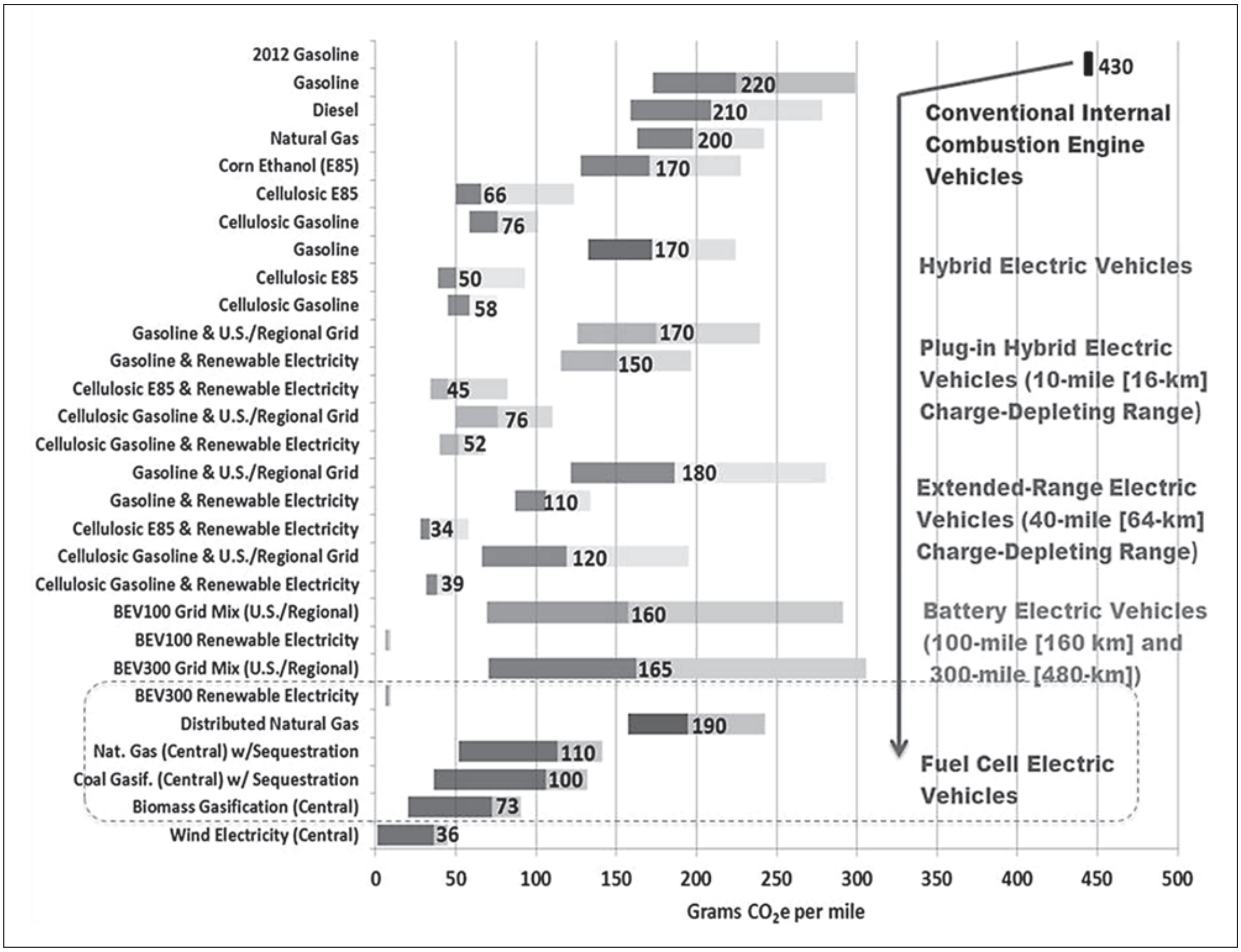

FIGURE 2 Well-to-wheels emissions for diverse vehicles and fuels. Different vehicle types are listed along the vertical axis starting with a baseline 2012 gasoline vehicle, followed in descending order by various advanced vehicles of the future. The amount of carbon dioxide in grams per mile driven for each vehicle is shown on the horizontal axis. Numbers in the horizontal bars represent the base case and each end of the bar (distinguished by shading) represents the minimum and maximum estimate for carbon emissions based on assumptions for efficiency, fuel pathway, electricity mix, and technology advances. Data from Nguyen et al. (2013).

have repeatedly emphasized that FCEVs can eliminate conventional drive train components such as transmissions, axles, and mechanical linkages, potentially simplifying vehicle manufacturing (Burns et al. 2002).

Disadvantages

While fuel cells provide benefits in terms of performance, efficiency, response time, and emissions, there are also challenges, primarily associated with the hydrogen infrastructure required to fuel automotive fuel cells.

Enthusiasts point out that hydrogen has the highest energy content of all known fuels (33.3 kWh/kg or 120 MJ/kg), but this is accurate only on a mass basis (nearly 3 times more than gasoline). On a volumetric basis, the energy content in liquid hydrogen (2.36 kWh/L or 8.5 MJ/L) is nearly four times lower than that of gasoline, and gaseous hydrogen at 700 bar pressures is six times lower (Berry et al. 2004; McWhorter et al. 2011). Since hydrogen is typically stored on board FCEVs as a high-pressure gas, this adds cost and complexity both on the vehicle and at the refueling station.

Advocates also point out that hydrogen is the most abundant element in the universe. But molecular hydrogen cannot be found on earth: it is bound in the form of water and numerous other compounds, and although it can be produced from water, using electrolysis, the typical conversion efficiency of producing hydrogen from water is at most about 70 percent (NPC 2012), which means that for every unit of energy input, roughly a third is wasted.

With the pros and cons of various technologies, there is no single one that meets all current needs. A portfolio of options is needed to significantly reduce petroleum use and carbon emissions. While advanced combustion, hybrids, and electric vehicles are important to pursue, fuel substitution is essential to meet national goals.

Well-to-Wheels Emissions

Fuel cells have high electrical efficiencies—with up to 59 percent demonstrated in real-world driving (Wipke et al. 2012)—but because hydrogen production requires energy it is not sufficient to emphasize fuel cell efficiency alone. The energy input and associated carbon emissions involved in fuel production, delivery, compression, dispensing, on-board storage, and on-board use must be taken into consideration.

Figure 2 shows the total "well-to-wheels" emissions for a variety of vehicles using a range of assumptions for advanced future technologies such as FCEVs, incorporating both conservative and optimistic advances in each technology and the availability of renewable electricity projected in 2035 (Nguyen et al. 2013). The numbers in the horizontal bars represent the base case and each end of the bar represents the minimum and maximum estimate for carbon emissions based on assumptions for efficiency, fuel pathway, electricity mix, and technology advances.

According to the data depicted in Figure 2, an average conventional midsize light-duty passenger vehicle operating on gasoline emits roughly 430 grams of carbon dioxide per mile, whereas all the advanced technologies show potential for reduced emissions. In the case of FCEVs, even when using distributed natural gas at fueling stations to generate the hydrogen, the total well-to-wheels emissions is less than half that of conventional gasoline-powered vehicles (Nguyen et al. 2013). And if natural gas is used to produce hydrogen at a central plant that includes carbon capture, the total emissions can be significantly less.

Clearly the use of renewables for hydrogen production or for charging battery electric vehicles is needed to achieve the greatest reduction in emissions. The key challenge is to produce hydrogen in a clean, low-cost, and environmentally responsible way.

Costs and Technical Challenges

Production

More than 50 million metric tons of hydrogen are produced worldwide, primarily by steam methane reforming of natural gas (DOE 2013a). Most of it is used in petroleum refining (to reduce sulfur content) and ammonia production.

With the large central production of hydrogen from natural gas, the cost of hydrogen is less than \$2/kg (NPC 2012). This equates to about \$2 per gallon gasoline equivalent (gge) because in terms of energy content (i.e., lower heating value), 1 kg of hydrogen is about the same as 1 gallon of gasoline (a convenience of nature so no conversion is needed). Hydrogen must also be produced from renewable sources at a sufficiently low cost to be competitive with gasoline and other fuels.

Delivery

Although hydrogen production costs from natural gas at large central plants may be low (particularly since shale gas development has enabled a drop in feedstock costs), the hydrogen still needs to be transported, compressed, and dispensed at a refueling station for use in vehicular storage tanks. The additional cost of these steps can be as high as \$3/gge, even at volume (Parks et al. 2014), resulting in a hydrogen cost of about \$5/gge dispensed at the pump (untaxed) even if produced at scale and using optimistic assumptions. In practice, at today's low volumes, the cost is substantially higher and varies depending on supplier, region, and application. Moreover, because compressors have not achieved consistent reliability, stations have to have more than one to ensure that customers can get the fuel they need when they need it.

A key challenge is to produce hydrogen in a clean, low-cost, and environmentally responsible way.

Storage

The estimated cost of a vehicular carbon fiber compressed hydrogen storage system at 700 bar is about \$3,000 if manufactured at 500,000 units per year—or more than \$6,000 at volumes of 10,000 units per year, even with optimistic assumptions (James et al. 2012). Compression is a key contributor to cost, and therein lies a key challenge: to carry a sufficient mass of hydrogen on board a typical passenger car (roughly 5 kg) and achieve a driving range of at least 300 miles, automakers are pressurizing it to 700 bar (about 700 atmospheres or 10,000 psi, the pressure agreed on by major global automakers). Safety requirements add cost as the tanks must be built to withstand more than twice their fill pressure (or more than 1,400 atmospheres of hydrogen) and undergo drop tests, bonfire tests, and even gunfire tests to ensure safety.

Fuel Cells

To be competitive with gasoline internal combustion engines, an automotive fuel cell system must cost $30/kW or less; the DOE has set a target of $40/kW by 2020 if produced at scale for early markets. However, based on state-of-the-art technology demonstrated in the laboratory (not yet in FCEVs), the projected cost if manufactured at high volume—500,000 units per year—is about $55/kW (Spendelow and Marcinkoski 2013). The current rate of production is substantially lower, resulting in a much higher unit cost of $280/kW, based on automaker references (Greene and Duleep 2013), which should be reported in conjunction with the high-volume projection. One of the key contributors to cost is platinum, the primary catalyst required for the electrochemical reaction. As discussed below, alternative materials are being studied.

Last, although performance and power density have been steadily improving, the durability of fuel cells does not yet meet the target of 5,000 hours or 150,000 miles, the expectation of today's automobile driver.

Recent Progress in Fuel Cells

Despite the challenges, significant progress has occurred, especially over the last decade, spurred by both government funding and private sector developments.

Federal Funding and Commercial Adoption

On the government side, the DOE fuel cell program began in the mid-1970s with a small group of researchers and managers at a Los Alamos National Laboratory workshop, when the oil embargo had stimulated increased attention to alternative energy and fuel technologies. These innovative thinkers paved the way for what was to become DOE's Fuel Cell Technologies Office, which now funds a roughly $100 million annual portfolio of research, development, and demonstration (RD&D) activities through universities, industry, and national laboratories, enabling innovations now being implemented in commercial systems for various applications.

In DOE's Office of Energy Efficiency and Renewable Energy (EERE) fuel cell activities have enabled more than 450 patents, the introduction of 40 commercial technologies in the market, and 65 emerging technologies that are expected to be market ready in 3–5 years (DOE 2013b). In addition to funding RD&D activities, EERE has cost shared the deployment of roughly 1,600 fuel cells for backup power at cell phone towers and for forklifts, resulting in industry purchases of more than 11,000 fuel cells (Devlin and Kiuru 2013a,b).

Furthermore, major companies such as FedEx, Walmart, Sysco, Wegman's, and Coca-Cola are beginning to purchase fuel cell forklifts for their warehouses, and Sprint, AT&T,

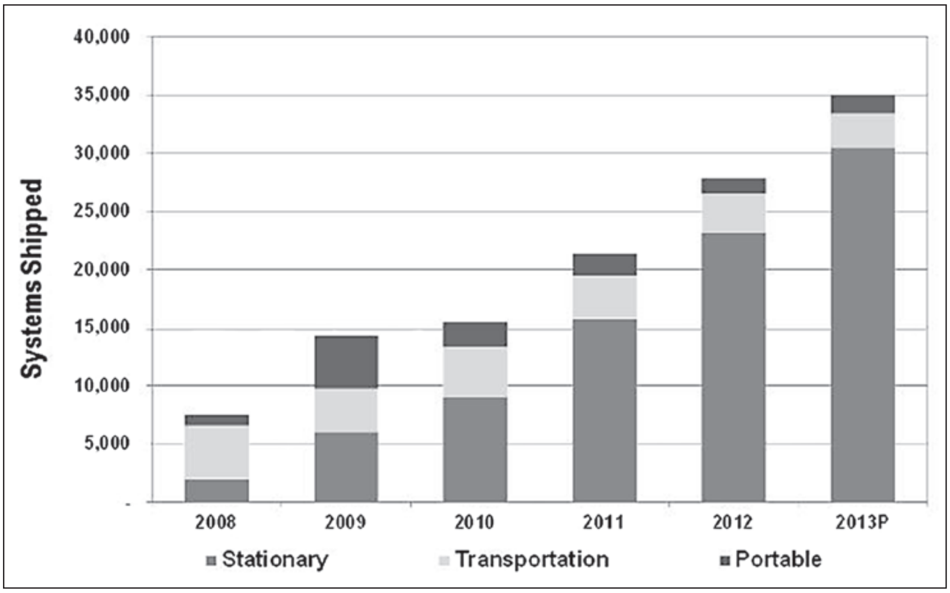

FIGURE 3 Fuel cell systems shipped (world markets), by application, 2008–2013P. Data are projected (P) for 2013. Stationary applications include residential fuel cells (primarily deployed in Japan) and large industrial fuel cells. Transportation applications include fuel cell forklifts. Portable power applications include fuel cell battery chargers for portable electronics. Data from Navigant, reported in Satyapal (2014).

and others are deploying fuel cell backup power units for their cell phone towers, all of which will create demand for a hydrogen infrastructure. In addition, large commercial and industrial buildings as well as data centers are using fuel cells for reliable power or combined heat and power. Figure 3 shows that fuel cells are no longer a laboratory research project: an estimated 35,000 units were shipped worldwide in 2013—up from about 15,000 just four years earlier—primarily in the stationary fuel cell market for combined heat and power (Satyapal 2014).

Materials and System Innovations

The platinum group metal (PGM) loading in PEM fuel cells has decreased by 2 orders of magnitude since the 1960s and 1 order of magnitude since the mid-1980s (Spendelow and Papageorgopoulos 2011). Advances such as nanostructured thin films by 3M and core-shell catalysts by Brookhaven National Laboratory (which contain a less expensive core metal such as nickel and a layer of platinum skin or alloy) have contributed to recent progress. Based on these and other advances, automotive fuel cell cost has decreased approximately 30 percent since 2008 and 50 percent since 2006 (Spendelow and Marcinkoski 2013).

Other innovations have paved the way for greater interest in hydrogen and fuel cell technologies. For example, DOE and state agency and private sector partners funded the demonstration of the world's first "trigeneration" system, a 300 kW, high-temperature, molten carbonate fuel cell that can convert biogas or natural gas to power, heat, and hydrogen. This system provides three simultaneous coproducts for use across sectors: stationary power generation, industrial or building heating and cooling, and hydrogen for transportation or other applications such as backup power or disaster mitigation. The system was demonstrated at a wastewater treatment plant and could be useful at other sites such as sewage treatment plants and landfills as well as numerous industrial facilities.

Certain fuel cell systems can also be used to separate/purify carbon dioxide to enable carbon capture. If tied to relevant future electricity generation, transmission, and storage infrastructure, a more holistic approach for hydrogen generation (e.g., trigeneration or natural gas reforming) could be coupled with local capture and utilization of carbon byproducts.

Hydrogen can also be used to enable the more widespread use of intermittent renewables such as solar or wind, electrolyzing water and storing the hydrogen for use either as a fuel or feedstock or to feed back to the grid via turbines or fuel cells to generate electricity. A number of such projects are under way at a large scale in Germany and other countries that have substantial deployment of renewables.

More Research Is Needed

The widespread commercialization and acceptance of hydrogen and fuel cell technologies will depend on advances enabled by further research and development (R&D). The cost of hydrogen from renewables and low-carbon sources must be reduced to meet the DOE target of $4/gge by 2020. Innovative approaches such as direct photoelectrochemical conversion of water to produce hydrogen, biological (including photobiological) approaches, and high-temperature thermochemical methods that can use heat from either nuclear or solar power are just some of the technologies that require more R&D. Although preliminary research (Elgowainy et al. 2014) shows that water and environmental impacts can be minimal, strategic and well-defined studies are necessary to ensure production of the required amount of hydrogen regionally with minimal ecological impacts.

Automotive fuel cell cost has decreased approximately 50 percent since 2006.

Once hydrogen is produced at a large scale, high-pressure tube trailers can reduce the cost of compression at the station and provide a viable option in the near to midterm. However, in the long term hydrogen pipelines will need to be built—currently only 1,200 miles of hydrogen pipeline exist in the United States, compared to more than 1 million miles of pipeline for natural gas (USDRIVE 2013).

For hydrogen storage, 700-bar tanks allow market entry with a 300-mile driving range for several types of vehicles, but low-pressure materials–based options would enable all vehicle platforms to achieve that range and without the infrastructure challenges associated with delivery of high pressure to the vehicle. Regardless of the type of technology used, codes and standards must be developed to allow the smooth market entry and social acceptance of hydrogen.

Fuel cell technologies also require more R&D to reduce or even eliminate PGM content without compromising performance or durability. From a vehicle systems perspective, one approach may be to use a small fuel cell (e.g., 8 kW rather than the nominal 80 kW) for an FCEV in conjunction with a larger battery as a range extender to allow the fuel cell to operate at constant load. This approach would enable greater durability and provide the extra driving range that BEVs cannot provide with smaller amounts of hydrogen at pressures lower than 700 bar. These and other innovative options should be considered even as early models are provided to customers.

Summary and Outlook for the Future

With carmakers already announcing plans for commercial FCEVs—and Hyundai already leasing the first production-volume FCEV in California as of June 2014—the industry is poised to make headway in the next few years, both nationally and internationally.

In 2013 DOE and industry stakeholders launched H2USA, a public-private partnership of more than 30 federal and state government agencies, global carmakers, hydrogen providers, trade associations, and other stakeholders committed to the deployment of hydrogen infrastructure. In May 2014 the California Energy Commission announced nearly $47 million in new funding for an additional 28 stations in the state, with a total of close to 50 to be completed before the end of 2015. Hawaii and Massachusetts are also developing scenarios for hydrogen infrastructure, and eight states (California, Connecticut, Maryland, Massachusetts, New York, Oregon, Rhode Island, and Vermont) recently signed a memorandum of understanding for 3.3 million zero-emission vehicles on the road by 2025.

On the international front even more aggressive plans are being made. Japan and Germany have announced plans for 100 stations each by 2015 and public-private partnerships to assess options for a much greater number in the coming years. The International Partnership for Hydrogen and Fuel Cells in the Economy, which includes the United States and 16 other countries as well as the European Commission, was established in 2003 to coordinate activities and accelerate progress toward widespread commercialization of hydrogen and fuel cell technologies.

There has been significant progress over the past decade, but sustained efforts in both RD&D and deployments are needed to continue the progress and enable the environmental, economic, and energy security benefits that could be realized with hydrogen and fuel cell technologies.

Acknowledgments

The author thanks the many researchers, stakeholders, and managers that are part of the DOE Hydrogen and Fuel Cells Program.

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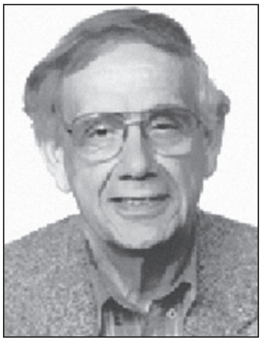
The federal government is responsible for disposal of US spent nuclear fuel and should proceed with plans for a deep geological repository to accommodate the growing SNF inventory.

Disposal of US Spent Nuclear Fuel



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Salomon Levy

The disposal of all US spent nuclear fuel (SNF) is the responsibility of the federal government. That decision was made in the 1950s by the Atomic Energy Commission and it still applies.

In 1976, however, US presidential candidates agreed that separation of plutonium (Pu) from SNF should be deferred indefinitely because of proliferation concerns, and that policy was implemented as a presidential order in April 1977. The result is that the commercial SNF inventory continues to grow; when storage capacity is exceeded, it will be shifted to interim storage facilities, and the US government will pay for those storage costs from its receipt of $1 per megawatt-hour of contained SNF energy for disposal.

Background

US history with plutonium started with the decision to produce it for nuclear bombs at Hanford and Savannah River in the early 1950s. The required Pu separation process produced extensive volumes of liquid high-level waste (HLW) that were stored in tanks and were rather costly to maintain to prevent leakage.

In the late 1970s the availability of low-cost uranium encouraged US electrical nuclear power plants to use once-through fuel cycles for economic reasons; the resultant SNF is stored in water pools at the plant to handle its decay heat until it can be turned over to the government for disposal.

That disposal was anticipated to be in deep geological repositories (DGRs) after appropriate approvals of their safety. But no DGR has been implemented and the US SNF stockpile continues to grow at the rate of about 2,000 metric tons per year, with requirements for storage depending on the government timing for its disposal.

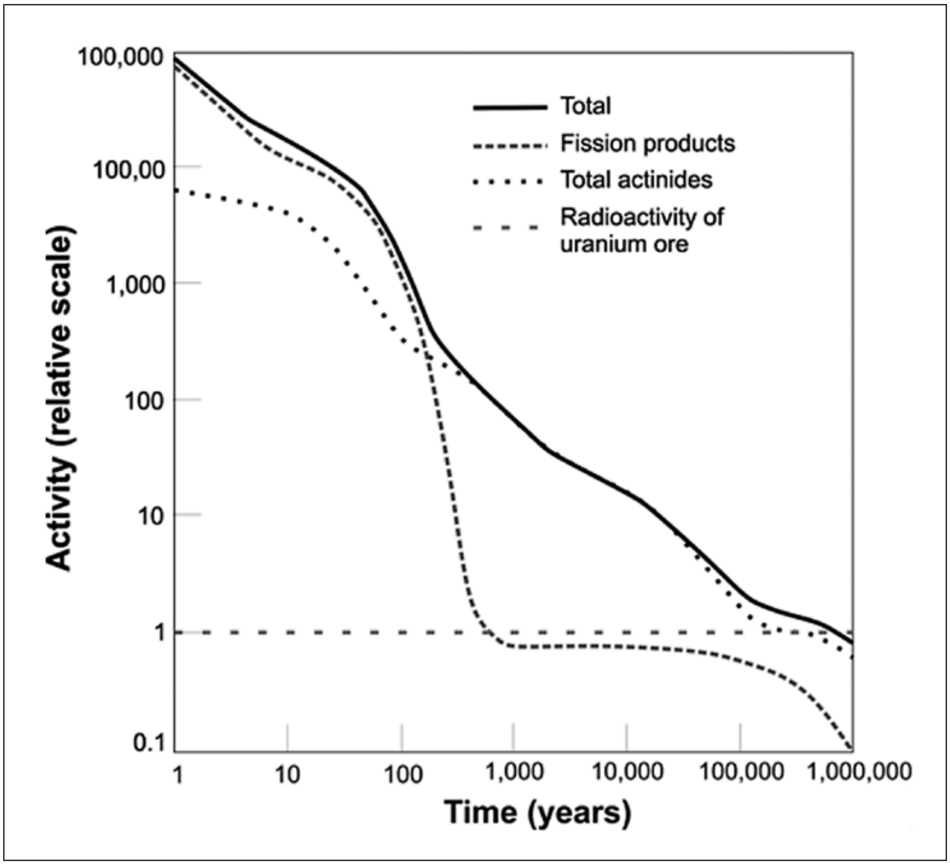

FIGURE 1 Radioactivity of used fuel relative to natural radioactivity of uranium ore as a unitless ratio. Time is shown in years since the removal of used fuel from a pressurized water reactor. Reprinted from Cherry et al. (2014).

Radioactive Content

Over the years the radioactivity of US nuclear power plant fuel has increased significantly both to reduce electrical generation costs and to achieve the current ability to generate about 20 percent of the nation's electricity. I remember that at the first commercial nuclear boiling water reactor (BWR), Dresden 1 (1960–1978), SNF radioactivity was limited to 5,000 megawatt-days per metric ton for safety reasons. In contrast, pressurized water reactor (PWR) fuel is now discharged with radioactive content or exposure in excess of 50,000 megawatt-days per metric ton of SNF.

The high radioactivity content in SNF relative to the natural radioactivity of uranium is plotted in Figure 1 (Cherry et al. 2014), showing that the ratio will approach the value of 1 only after 100,000 to 1,000,000 years. However, accepted engineering practice is to suspect all long-term predictions beyond 10,000 years because their uncertainties increase with time and become too large to be trusted.

It is important to note that Figure 1 does not apply to all US discharged power plant SNF because radioactive contents vary with plant operating conditions and how the fuel was used. Also, there are amounts of SNF discharged from the earliest operating plants or discharged prematurely (for a variety of reasons) that may have ratios of radioactive content to that of natural uranium much closer to 1 after about 10,000 years. The disposal of these amounts of SNF in DGRs may be worth pursuing even though approval by some of the involved parties may be difficult. Such attempts are urged and recommended both to establish and address opposition views and to get early experience with SNF disposal in DGRs.

Disposal Options

SNF could be reprocessed to obtain its Pu and usable uranium (U) for reuse or turned over to the US government for disposal after adequate removal of its decay heat. The United States tested the closed fuel cycle approach to reprocessing SNF, recycling Pu, and reusing the U fuel, as illustrated in Figure 2. Reloads were carried out for both BWRs and PWRs but discontinued because they could not compete with the once-through fuel cycle.

At Savannah River the HLW is separated into two streams: the highly radioactive products (primarily strontium and cesium) and the remaining low-level waste. The radioactive products are to be combined

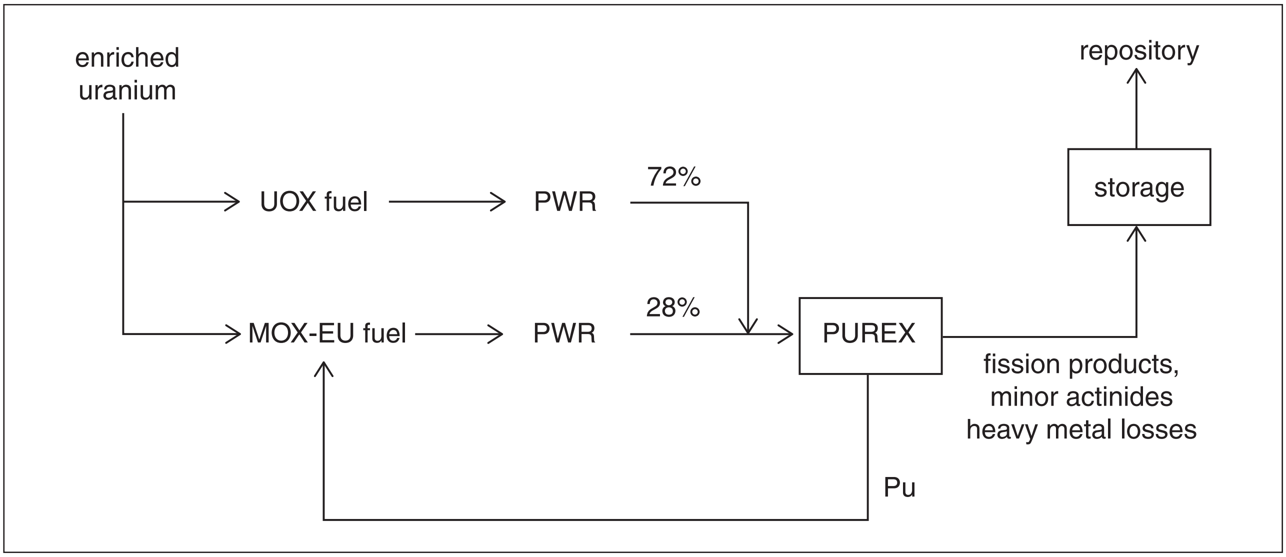

FIGURE 2 Plutonium (Pu) recycle for a pressurized water reactor (PWR). EU = enriched uranium; MOX = mixed oxide; PUREX = plutonium uranium extraction; UOX = uranium oxide.

with glass-forming material to produce a glass molten mixture that is solidified into stainless steel canisters for eventual disposal in DGRs.

Liquid metal fast breeder reactors (LMFBRs) were once considered an attractive nuclear alternative and a major US Department of Energy (DOE) program was carried out at the Idaho National Laboratory, where two experimental breeder reactors (EBRs) operated successfully. That program included the coupling of EBR-2 to light water reactors (LWRs) and the development of a pyro-processing technology to deal with LMFBR spent fuel disposal. However, the program was abandoned because the LMFBR electricity production costs were judged excessive and not able to compete with LWR-produced electricity. The United States is participating in an LMFBR program in South Korea but with no intent to restart such an effort in this country.

France is the world leader among nations in avoiding underground Pu disposal. For example, AREVA, a French nuclear power engineering company, can operate with a full core of mixed Pu-U fuel and use an advanced fuel assembly (named CORAIL) that is capable of multiple Pu recycling. The anticipated results of these efforts are depicted in Figure 3, which shows the projected French Pu inventory with different reload strategies. However, it is important to note that France can pursue any Pu strategy it desires because its charges for electricity are determined by the government and not subject to competition as they are in the United States. In other words, US Pu recycling must be able to compete with nonnuclear generation of electricity, and that objective is not readily satisfied.

Regulatory Delays

The US Nuclear Regulatory Commission (USNRC) review of disposal safety at Yucca Mountain has been restarted by the courts and the findings will be of great interest when published. While it would be inappropriate to predict the USNRC conclusions, it is worthwhile to recall that DOE was originally assigned responsibility in 1982 and that Yucca Mountain was selected because it was judged the best available site. Years have passed and nearly $18 billion has been spent to justify the site's safety—which has already been established by an independently reviewed, published total system project analysis.

I believe the potential USNRC comments can be satisfactorily addressed, but the challenge is in getting the government to proceed with SNF disposal instead of continuing to delay. A preliminary approach should be developed and needs for legal and technical personnel identified. The program will face opposition from the current president and the Senate while having the support of the House and nuclear plant owners. It is hoped that a meeting of the opponents could be arranged to find a compromise and to avoid another intervention by the courts.

A logical compromise might be to agree on limited SNF disposal at Yucca Mountain with the provision to remove the SNF if the release of radioactivity exceeds

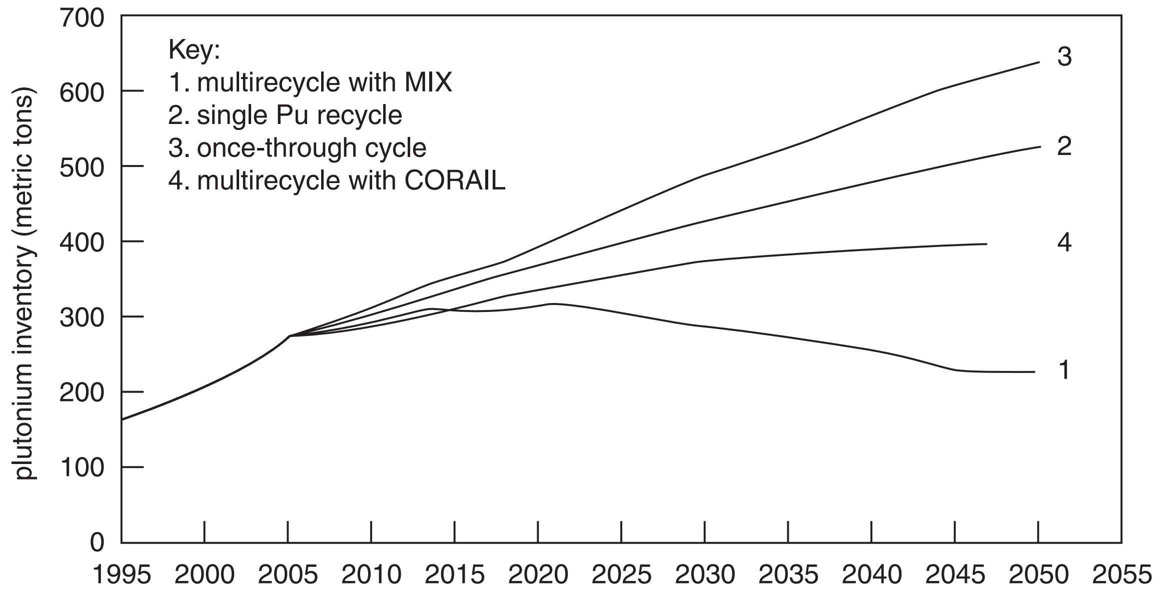

FIGURE 3 Plutonium (Pu) inventory and recycling in France, 1995–2055. CORAIL = French advanced fuel assembly capable of multiple Pu recycling; MIX = ARP4, French advanced fuel assembly to be developed by 2030.

agreed-upon levels. Some benefits in terms of roads and construction may be needed and Nevada technical personnel should be welcome to participate in the safety evaluations and to voice their concerns.

Conclusions

Disposal of SNF from the earliest operating plants and of SNF discharged prematurely should be pursued at Yucca Mountain. Safety documents should be submitted to the US Nuclear Regulatory Commission for review and approval. If the process is denied or stopped, appeal to the courts should follow to secure disposal.

The process should be extended to other SNF starting with the lower fuel exposures and expanding to cover all SNF.

SNF owners need to have strong legal and technical teams to support this process and ensure its success.

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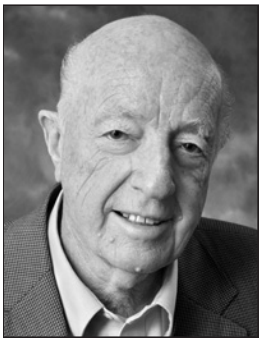
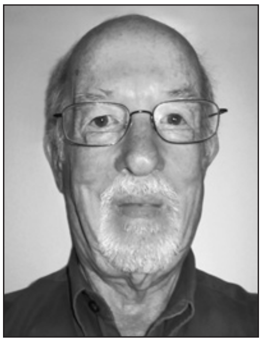
Technical advances that support the geologic disposal of high activity waste must be complemented by progress in policies, management improvements, and public engagement.

Technical Advances for Geologic Disposal of High Activity Waste



B. John Garrick



Carlos A.W. Di Bella

B. John Garrick and
Carlos A.W. Di Bella

"High activity waste" consists of spent nuclear fuel (SNF)—fuel that has been withdrawn from a nuclear reactor following irradiation—and high-level radioactive waste (HLW), the highly radioactive material resulting from the reprocessing of SNF. The primary inventory of SNF in the United States is from commercial nuclear power plants. There are approximately 70,000 metric tons[1] of commercial SNF assemblies (an example of a commercial nuclear fuel assembly is illustrated in Figure 1)[2] in the United States.

B. John Garrick (NAE) is a consultant in nuclear technology and risk assessment, former chair of the US Nuclear Waste Technical Review Board (NWTRB), and former member and chair of the US Nuclear Regulatory Commission's Advisory Committee on Nuclear Waste. Carlos A.W. Di Bella is a consultant in the areas of nuclear waste management and disposal and carbon capture and sequestration and a former member of the NWTRB senior professional staff.

This paper is based in part on a 2011 NWTRB report (NWTRB 2011), of which Dr. Garrick was the major contributor and Dr. Di Bella the principal compiler and editor. The views in this paper are those of the authors and not necessarily those of their current or past affiliations.

[1] "Metric tons" here is short for metric tons of initial heavy metal, i.e., metric tons of uranium and higher-atomic-number elements before irradiation in a nuclear reactor.

[2] About two-thirds of US commercial power reactors are pressurized water reactors (PWRs). A typical PWR nuclear fuel assembly has dimensions of approximately 21 cm × 21 cm × 4 m and contains approximately 0.5 metric ton of fuel. The balance of US commercial power reactors are boiling water reactors.

Almost all these assemblies are stored underwater in pools or in dry storage at the reactor sites where the SNF was generated (Pietrzyk 2014).

In addition, the federal government owns approximately 2,500 metric tons of SNF from its defense production, naval nuclear propulsion, research and development, and other activities. The government also has approximately 350,000 cubic meters of HLW from reprocessing for defense purposes, most of which is in large underground tanks in liquid, sludge, or solid forms that will require conversion to an inert solid form prior to disposal.[3]

Before its termination by the Obama administration in 2009,[4] the plan was to dispose of the majority of the nation's high activity waste in a mined geologic repository at Yucca Mountain (Figure 2)—assuming its long-term safety could be established to the satisfaction of the US Nuclear Regulatory Commission (USNRC)—with a second repository to follow upon reaching the capacity of Yucca Mountain.

The purposes of this paper are to highlight some of the accomplishments of the Yucca Mountain project, to outline developments since its termination, and to discuss specific actions for moving forward with the development of a mined geologic repository in the United States.

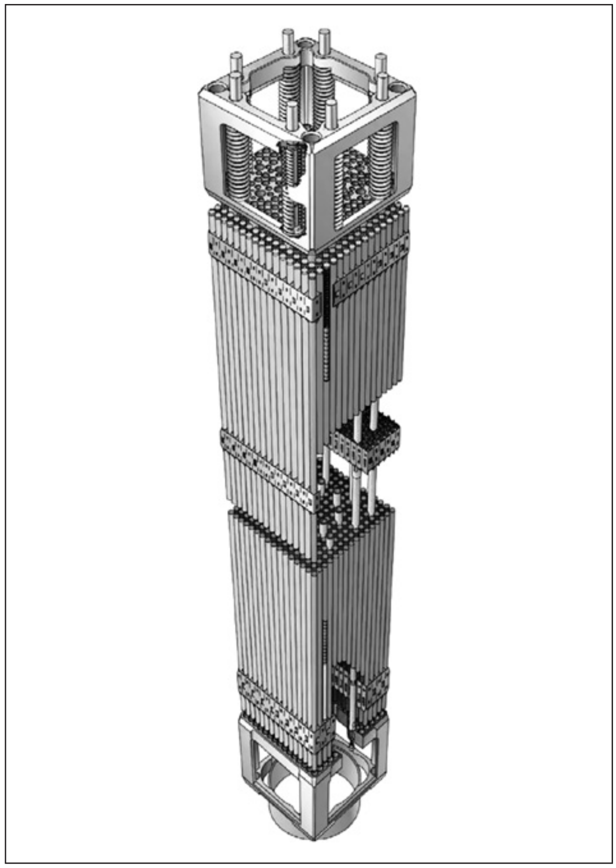


FIGURE 1 Westinghouse pressurized water reactor nuclear fuel assembly. Downloaded June 21, 2014, from http://me1065.wikidot.com/fuel-assemblies-in-nuclear-reactors.

Technical Advances before Project Termination

Among the advances made by the Yucca Mountain project were a greater fundamental understanding of water flow in unsaturated fractured rock[5] in arid regions; models to account for runoff, evaporation, and plant transpiration; a better understanding of the effects of capillary forces and other parameters; mapping techniques for locating faults and past volcanic activity; greatly improved understanding of seismic and igneous hazards; improved, state-of-the-art methods for eliciting information from experts; and design alternatives for controlling the temperatures in the repository.

Engineered Barriers

Any repository has two parts: the engineered (or man-made) system and the natural system. The Yucca Mountain project relied heavily on the engineered system to first prevent, then retard entry of waste into the natural system for extended periods. Because an engineered system is designed to a detailed specification and built to exacting standards it is associated with less uncertainty than a natural system, which has inherent heterogeneities that are difficult to fully characterize over many cubic kilometers of geology.

There is increasing evidence that engineered barriers can be designed and constructed to last for very long periods, possibly hundreds of thousands of years or more. Such a delay dramatically reduces the radiotoxicity of

[3] A small fraction of the HLW has been converted to inert solid form already. The total radioactivity of the HLW is less than a few percent of the total radioactivity of the commercial SNF.

[4] On March 11, 2009, Secretary of Energy Steven Chu stated, "Both the President and I have made clear that Yucca Mountain is not a workable option.…" Statement before the Senate Committee on the Budget, Washington, DC, available at www.energy.gov/sites/prod/files/ciprod/documents/3-11-09_Final_Testimony_%28Chu%29.pdf. However, "termination" is not strictly correct. Although the Yucca Mountain project has been completely destaffed and defunded, unless and until changes are made to the Nuclear Waste Policy Act, as amended, development of a repository at Yucca Mountain is still the law of the land. The project was terminated for social and political reasons (GAO 2011), not cost or technical ones.

[5] The unsaturated zone is essentially the rock above the water table.

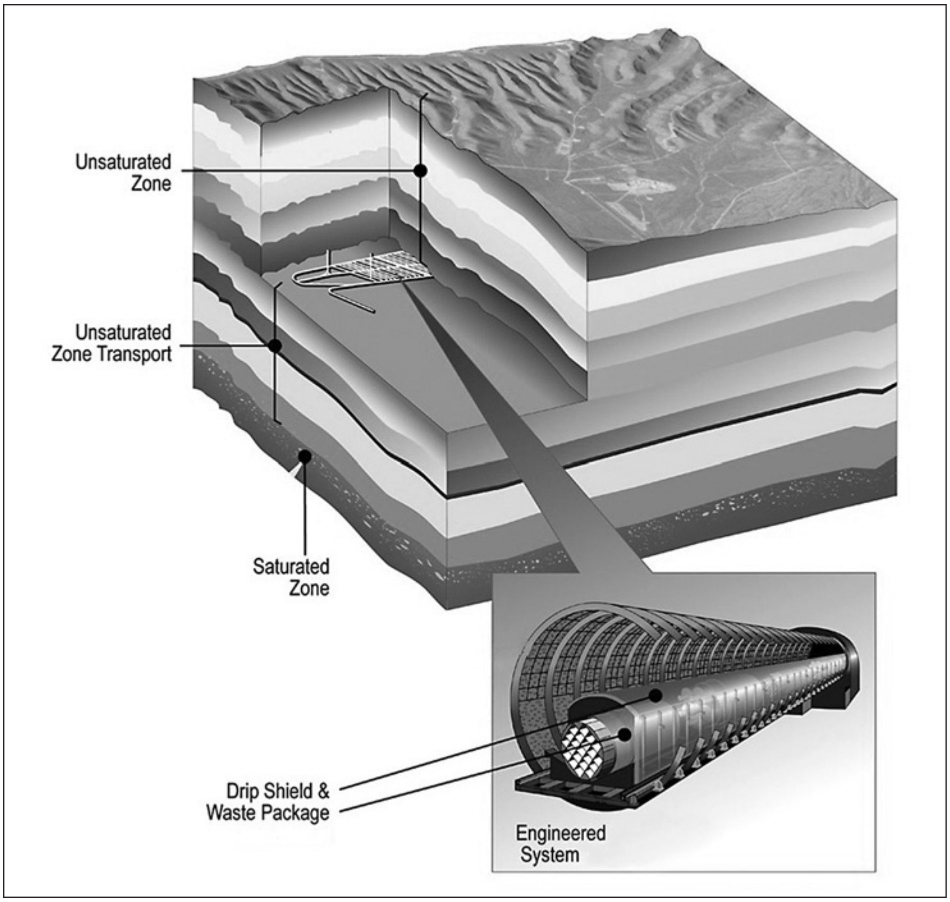


FIGURE 2 Artist's conception of mined geologic repository proposed for Yucca Mountain. Adapted from an image on the Esmeralda County (NV) Repository Oversight Program website, at http://esmeraldanvnuke.com/Graphics/00199dc_021d_300dpi.jpg.

the waste via radioactive decay and simplifies the chemistry of the waste that might enter the natural system, thus enhancing the predictability of the long-term performance of a repository.

The key to modeling the degradation of the engineered system is a fundamental understanding of the physical and chemical environment provided by the natural system for the engineered system over very long time periods. The radionuclide source term[6] may be the most important contributor to the performance of a geologic repository—and its contribution may be the most difficult to quantify.

The Total System Performance Assessment

One of the major achievements of the Yucca Mountain project was the Total System Performance Assessment for the License Application (TSPA-LA) that was included in the Department of Energy's (DOE) application submitted to the USNRC in 2008. As noted in the US Nuclear Waste Technical Review Board report (NWTRB 2011, p. 49), the "TSPA-LA represented the culmination of the most thorough study of the performance of a geologic repository for high activity waste ever performed by US scientists and engineers."

The period of performance for TSPA-LA was 1 million years. DOE, its contractors, and the US Geological Survey developed models for all the major components of the repository including the engineered barrier system, the hydrogeologic unsaturated and saturated zones, and the biosphere. The models were abstractions from major studies performed on features, events, and processes (FEPs) associated with the repository, and the figure of merit was a probability-weighted radiological dose to humans. A major effort was made to quantify the contributions to uncertainty by propagating FEP uncertainties throughout the model. The results included the importance ranking of the contributors to the overall dose to humans.

The TSPA-LA had the benefit of the previously prepared performance assessment of the Waste Isolation Pilot Plant (WIPP) in Carlsbad, New Mexico,[7] and probabilistic risk assessments performed on nuclear

[6] "Source term" in this paper refers to the radionuclides that leave the engineered system and enter the natural system.

[7] US Title 40 CFR Part 191, Subparts B and C, Compliance Recertification Application for the Waste Isolation Pilot Plant (WIPP) Appendix PA-2009 Performance Assessment, US Department of Energy WIPP Carlsbad Field Office, New Mexico, 2009. Available at www.wipp.energy.gov/library/CRA/2009_CRA/CRA/Appendix_PA/Appendix_PA.htm.

power plants and other facilities, but there were scoping requirements not before encountered, of which the 1-million-year period of performance was obviously the most challenging.

Many lessons were learned from the TSPA-LA about doing probabilistic performance assessments involving very long term performance requirements. Despite its accomplishments, TSPA-LA had some deficiencies over the more mature probabilistic risk assessments for nuclear plants: first, it was compliance driven rather than a realistic evaluation focusing on the more fundamental question, "What is the risk?" A second important deficiency was the use of weighted probabilities to present the results, rather than the more transparent presentation of probability *and* consequences, an approach used in the quantitative risk assessment field.

Advances since Project Termination

There have been important policy and technical advances in high activity waste management and disposal since the administration's decision to terminate the Yucca Mountain project.

Policy Advances

On the policy front, in early 2010, at the request of President Barack Obama, Secretary of Energy Steven Chu chartered the Blue Ribbon Commission on America's Nuclear Future (BRC), a panel of 15 distinguished individuals charged with conducting a comprehensive review of policies for managing the "back end" of the nuclear fuel cycle, including all alternatives for high activity waste storage, processing, and disposal. The commission issued its final report in January 2012 (BRC 2012), with a strategy consisting of eight key elements, four of which were significantly different from the strategy followed since enactment of the Nuclear Waste Policy Act in 1982 and its amendments in 1987:

1. A new, *consent-based* approach to siting future nuclear waste management facilities.
2. A new organization dedicated solely to implementing the waste management program and empowered with the authority and resources to succeed.
3. Better access by the developer/implementer of the waste management system to the funds nuclear utility ratepayers are providing for the purpose of nuclear waste management.
4. Prompt efforts to develop one or more consolidated storage facilities.

Secretary Chu responded to the commission's report with a January 2013 report that endorsed the principles underpinning the commission's strategy and presented the following plan (DOE 2013):

- Site, design, license, construct, and begin operations of a pilot interim storage facility by 2021 with an initial focus on accepting SNF from shut-down reactor sites;
- Begin operations by 2025 of a larger interim storage facility with sufficient capacity both to provide flexibility in the waste management system and to accept enough SNF to reduce government liabilities; and
- Make sufficient siting and site characterization progress to facilitate the availability of a full-scale geologic repository by 2048.

A new, consent-based approach is recommended for the siting of future nuclear waste management facilities.

Stops and Starts

In June 2013 a bipartisan group of four senators filed a bill that, if enacted, would implement much of the plan outlined in the DOE report.[8] Although hearings were held on the bill it has otherwise languished, and no companion bill has emerged in the House of Representatives. Passage of a nuclear waste bill by January 3, 2015—the last day of the 113th Congress—seems extremely unlikely because the topic does not appear to have high legislative priority. DOE, for its part, has been doing nothing visibly to advance nuclear waste policy legislation since issuing its January 2013 report.

The USNRC accepted DOE's application for a license to construct a repository at Yucca Mountain on September 15, 2008, and immediately began reviewing it (USNRC 2009), but suspended the review in 2010

[8] The Nuclear Waste Administration Act of 2013 (S. 1240), sponsored by Sen. Ron Wyden (D-OR) and cosponsored by Sens. Lamar Alexander (R-TN), Dianne Feinstein (D-CA), and Lisa Murkowski (R-AK), was introduced June 27, 2013.

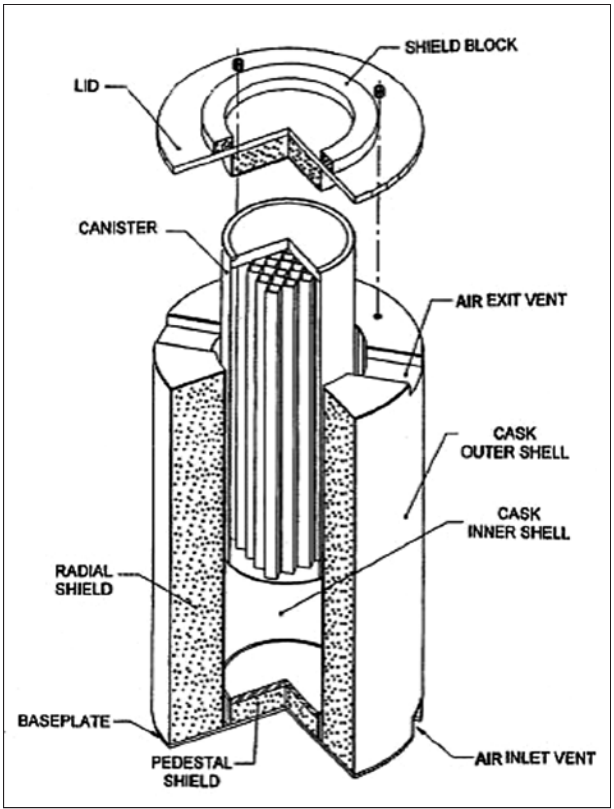


FIGURE 3 Cutaway of Holtec Hi-Storm© dry storage system. Source: USNRC (2001).

after the administration's decision to terminate the project. On August 13, 2013, the US Court of Appeals for the DC Circuit rebuked the USNRC for flouting the law by discontinuing the review and, in effect, ordered the agency to resume consideration of the license application using funds remaining (~$11 million) from prior year appropriations.[9] USNRC technical staff complied and expect to issue safety evaluation reports in early 2015 (Piccone 2014).[10] The safety evaluation reports will be extremely valuable for any future repository because they will provide an explicit example of how the USNRC technical staff reviews a license application and reaches technical conclusions.

Technical Advances and Research

On the technical front, a relatively small amount[11] of generic (i.e., not site-specific) research on high activity waste management and disposal continues under the supervision of the DOE Office of Nuclear Energy. The current emphasis of the research appears to be on (1) direct repository disposal of large, dual-purpose canisters containing commercial SNF (Figure 3), (2) dry storage of high-burnup commercial SNF, and (3) an integrated waste management system—including consent-based siting. Direct disposal of canisters loaded with commercial SNF in a repository without opening them would avoid significant costs, worker exposure, generation of low-level radioactive waste, and a waste of resources as the canisters would not be reusable because of radioactive contamination. Thus it is important that DOE is looking carefully at the practicality of this option. We have no doubt that direct disposal is technically feasible; the question is whether it is practical.

The Office of Nuclear Energy issued a roadmap in 2011 to guide DOE's waste management R&D program (DOE 2011). The roadmap should be revised to reflect the final BRC report, DOE's response to that report, and the R&D program's current emphasis.

Research is needed to better predict the repository emplacement environment for long time periods. Knowledge of the physical and geochemical conditions of this environment is critical for modeling waste degradation and mobilization confidently. Factoring such detail into the choice among geologic media could alter the priorities on which medium to favor. It is not clear, however, how much the DOE research program is considering the effect of the mix of engineered barriers, waste packages, waste forms, and geologic media on the evolution of the emplacement environment.

There also continues to be some research on the impacts of partitioning and transmutation (P&T) and reprocessing on geologic disposal. Studies by entities such as the National Research Council (NRC 1996) and the Swedish Nuclear Fuel and Waste Management Company (SKB 2004) appear to indicate lack of technology or economic incentive to deploy P&T in the near or medium term. Reprocessing would reduce the size needed for a repository but would not elimi-

[9] US Court of Appeals for the District of Columbia Circuit, On Petition for Writ of Mandamus, No. 11-1271, August 13, 2013.

[10] USNRC technical staff issued "technical evaluation reports" in 2011 after the review had been suspended. Although these reports are valuable, they lack any conclusions about whether in the staff's opinion the repository would meet the safety standards in the regulations. The safety evaluation reports will contain those conclusions.

[11] Approximately $45–75 million/year, roughly a tenth to a fifth of the average annual expenditures on the Yucca Mountain project for the two decades ending in 2008.

nate the need for a repository. Furthermore, adoption of reprocessing in the United States does not appear to be economically advantageous for the current fuel cycle and there are significant concerns about proliferation of nuclear materials associated with reprocessing.

Moving Forward

DOE's January 2013 plan focuses on storage in the near term and delays the opening of a repository until 2048. We know of no careful, objective study comparing the technical, safety, and cost advantages and disadvantages of DOE's plan compared to other plans. Such a study is needed before proceeding with any plan.

We believe the following three views are shared by the world technical community involved with the management and disposition of high activity waste:

1. **Geologic disposal is necessary regardless of the fuel cycle ultimately chosen.** No current technology or technology likely to be developed in the near future appears able to preclude the need to develop *some* geologic disposal capability.
2. **Geologic disposal is feasible.** Geologic disposal can isolate high activity waste from the human environment for as long as necessary—which could be as long as a thousand millennia or more. Furthermore, many locations and many geologic media—including clay, shale, salt, tuff, and crystalline rock—appear capable of doing the job.
3. **Public apprehension about geologic disposal and transportation of high activity waste is high and must be addressed.** Interestingly, this apprehension is not necessarily strongest in the communities that would host geologic repositories but in the regions and states in which those communities are located. Both Carlsbad, New Mexico, which hosts the WIPP repository for the disposal of transuranic waste,[12] and Nye County, Nevada, site of the Yucca Mountain repository, want sufficient assurance of the safety of the respective repositories, but otherwise appear to welcome them. The states that house or would house the repositories do not seem to have the same expansive view.

Our position, which is the same as that expressed by the NWTRB, is that the nation should keep a focus on a permanent solution to the disposal of high activity waste for the following reasons (NWTRB 2011, p. 69): "(1) a permanent solution is critical to building public confidence that there is a way of isolating nuclear waste radioactivity from the biosphere to acceptable levels; (2) given the long duration of the hazard of high activity waste, undue delay in a permanent solution could make tenuous a concept of waste management dependent on institutional stability; and (3) experience to date has indicated that deploying a permanent solution to isolating high activity waste could take decades."

We believe the following specific actions should be taken to keep the nation moving forward in finding a permanent solution to the disposal of high activity waste:

- Do not allow the loss of what has already been learned about geologic disposal; develop a deliberate and systematic process for capturing lessons learned into a formal knowledge base in the manner of a recent special issue on performance assessment (RESS 2014).

Develop a systematic site selection process that engages the public in a meaningful and productive way.

- Develop a site selection process that is systematic and based on the fundamental concepts of decision analysis while engaging the public in a meaningful and productive way.
- Develop a site characterization process that is interactive and strongly coupled with probabilistic performance assessments of the site to enable a truly risk-based foundation of knowledge, including uncertainties.
- Develop a transparent roadmap of the phases of a geologic disposal project including decision points, site characterization, design, licensing, construction, operation, and closure.

Importance of Local Engagement

Adopting a consent-based process for selecting a repository or consolidated storage site raises the question, "At what point would communities/states/tribes that would

[12] Transuranic waste contains more than 100 nanocuries of alpha-emitting transuranic isotopes with half-lives greater than 20 years per gram of waste, except for high activity waste.

host the prospective facility lose the right to veto the site?" The law applying to the Yucca Mountain project required that dissenting parties reject the site within 90 days of presidential approval of the site. President George W. Bush approved the site on February 15, 2002, and the state of Nevada formally rejected the site on April 8, 2002, but its veto was overridden by Congress on July 9, 2002.[13]

In our view, communities/states/tribes need some form of veto power during designated phases of any repository or consolidated storage project. This implies a much greater degree of transparency, openness, and candor on the part of the implementing organization than DOE afforded the Yucca Mountain project. In particular, in addition to or as part of any TSPAs submitted to the USNRC for compliance purposes, the implementing organization must simultaneously perform TSPAs that (1) extend to the time of peak dose, (2) include sensitivity studies so that the value of various components and parameters of the facility can be evaluated, (3) include FEPs that have a significant chance of occurring after 10,000 years (e.g., criticality), and (4) are realistic rather than conservative.

> *We believe the recommendation to move the disposal program from DOE to a new organization is an excellent one.*

Regardless of the political situation, the scientific and engineering community must be conscious of the importance of doing its work in a transparent, competent, and *understandable* manner to provide the public, decision makers, and, yes, politicians with the necessary information to assure them that major project decisions are being made appropriately and that public funds are being managed correctly. Thus, finding a process that minimizes the waste of public funds on major science and engineering projects that end up terminated for political reasons requires extensive interaction of those who have the knowledge about the project and those who have to lead the decision-making process.

Lessons from Yucca Mountain

The Yucca Mountain project was the responsibility of DOE. As a federal project, it was subject to the federal budgeting process and the links of that process to the ever changing political scene as well as the desire to spread the work among many different organizations geographically separated and not always happy to work with each other. Such a project environment rarely results in a tight and dedicated team, which is clearly needed for a project as complex as a first-of-a-kind, multimultibillion-dollar high activity waste transportation, management, and disposal system.

Probably the worst characteristic of the Yucca Mountain project was its inability to effectively transition in a reasonable period from a science project to an engineering project.[14] To be sure, science work had to be an integral part of the project throughout its duration. But our opinion is that the absence of a strong engineering culture and a truly engineering-based project structure greatly handicapped the decision-making process, the efficient movement of the project forward, and the implementation of best practices in engineering for meeting project goals.

It is difficult not to notice the extremely poor success rate of DOE major projects over the past several decades. They are often far past schedule and far over budget, if they work at all. How to organize and manage large, first-of-a-kind projects is not within our scope of expertise, but the need to study how DOE does this and to develop and analyze alternatives to the DOE approach is clear. Thus, we believe that the BRC recommendation to move the disposal program from DOE to a new organization is an excellent one. A compromise would be to separate the commercial waste from the defense waste, moving the commercial waste management to a new organization.[15]

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[13] See NWTRB (2003, p. 3) for citations and additional discussion.

[14] The transition was finally made soon after Edward ("Ward") Sproat became director of DOE's Office of Civilian Radioactive Waste Management, the office responsible for the Yucca Mountain project. He served in that position from May 2006 until January 2009.

[15] Defense HLW and commercial fuel need not be disposed of in the same kind of repository. For example, defense HLW could be disposed of in deep (3–5 km or more) boreholes, and commercial spent fuel in a mined geologic repository.

Finally, opportunities clearly exist to conduct research and analyses that could greatly facilitate the more efficient deployment of any future geologic disposal program. We are pleased that DOE has had the foresight to continue at least a modest amount of disposal research and development under the aegis of its Office of Nuclear Energy and that Congress has seen fit to fund it. This work and the people performing it will form the nucleus of any new US disposal program.

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An Interview with . . .

Richard Blanco, PE

Poet Richard Blanco speaks during the presidential inauguration on the West Front of the US Capitol January 21, 2013, in Washington, DC. Barack Obama was reelected for a second term as president of the United States. (Photo by Justin Sullivan/Getty Images)

Ron Latanision: Richard, we are really delighted that you're available to talk with us this afternoon.

Richard Blanco: My pleasure.

RL: I understand from **Sam Florman** that you and he have had some communication since he read a column about you in the *Boston Globe*.[1] Sam contacted us afterward, pointed out that you are a poet, and said, "You know, engineers do a lot of things beside engineer." The timing of Sam's communication was fantastic because Managing Editor Cameron Fletcher and I had been plotting to include a new column in the *Bridge* featuring the roles that engineers play in our culture and social fabric that go beyond building engineering systems that serve a societal purpose. Members of Congress have been engineers, and at least one president was an engineer. Sam's communication with us gave us an opportunity to introduce this new column with an interview with you. We've seen your resumé and the press material on your website (http://richard-blanco.com/), but I don't have a good feel for what kind of engineering you've done.

RB: I'm a practicing civil engineer. I graduated in 1991 from Florida International University with a BS in civil engineering and have worked at several companies, mostly with C3TS (now a part of StanTec). I've done everything from the glamour of sewage design to bridge hydrology, and dabbled a little in environmental engineering for the Florida Department of Environmental Protection (DEP). For about the past eight years I've focused mostly on what we call streetscaping or downtown revitalization projects in municipalities in south Florida—working with a town council or board and reenvisioning the whole streetscape, the feel of the town, and working with the community and with architects and mechanical engineers and electrical engineers. It's exciting because you get to see engineering interfacing with people's very lives, and there's a wonderful overlap with that and poetry as well—the idea of creating a sense of place, of creating a vision for a place, which obsesses my work as well, a sense of belonging, the idea of home and what that means. I got my PE license the same year I graduated with my MFA (1997), so I like to say I got my poetic license and my engineering license at the same time.

RL: Is your PE license still in effect?

RB: Yes, in Florida and I've been practicing until this last year and a half. I haven't been on call since I moved up to Maine but I've been working long distance with StanTec on an as-needed, on-call basis.

RL: I understand you had an early interest in science and math. Did you also have an interest in writing and the arts? Or how did that transition occur?

[1] The interview by *Boston Globe* correspondent Amy Sutherland ran on December 7, 2013; it's available at www.bostonglobe.com/arts/books/2013/12/07/bibliophiles-poet-richard-blanco/s2IU9GNexIVKdJD1SszJ6H/story.html.

RB: I didn't transition: I've practiced both all my life. I think that's a very important point to make—you can do more than one thing in your life if you want to. I was always a left brain, right brain kind of kid—got exactly the same scores on standardized tests between verbal and analytical—so that's part of why I can do what I do. As a child I was one of those students who was fascinated by everything; I would draw flowers and then I would draw propulsion systems for a new spaceship, I'd draw blueprints and then I'd draw landscapes, so I always carried both kinds of abilities.

The decision to study engineering had many dimensions. One of course is what my parents, being a working-class immigrant family, encouraged. And that's what society encourages—more traditional careers. Another part of that choice had to do with my sexuality; my grandmother was very homophobic, so if I had said I wanted to study poetry or English or anything that wasn't doctor, lawyer, or engineer, it wouldn't have gone over very well. Then of course there was the fact that I was actually great at math and loved it, it fascinated me. So that was my decision to study engineering.

And actually, I started writing because of engineering. Especially when I started working full time, realizing how much writing was involved—reports, studies, proposals, letters to permitting agencies.... I realized that to do your job effectively you had to translate almost everything into language. Even when writing notes on plans you had to use compression: you had to be precise [and] accurate [and] use as few words as possible. The same holds true for poetry, which can similarly be described as precise, accurate, compressed language.

I realized that language was engineered like everything else. How you write depends on your audience, on what tone you want to provide, and I became curious about language and started excelling at my job because of my writing skills. Then my right brain woke up and said "Hey, weren't we going to do something for me at some point in your life?" I started fooling around writing poetry just for fun, and eventually got more serious and more connected to it.

RL: Communication skills are so important in the everyday life of an engineer. If an engineer can't communicate with clients or colleagues, it's a real obstacle.

RB: Someone told me about a recent survey (from ASCE and some other organizations, I don't remember who did it) asking what was most lacking in engineering students when they graduated. At the top of the list was writing. When I used to get graduates right out of the university I'd say, "First we're going to learn how to write a sentence, then you can design something. Because now you can design something but you can't write a sentence about it."

I always like to say that engineering made me a better poet and poetry made me a better engineer. It's the idea of connecting with people and understanding that it's not just a set of plans but there are people involved in this process.

RL: You probably know about ABET, the accreditation board for university engineering curriculum. One of the major elements of the accreditation process involves ensuring that undergraduate engineers are taught to write and speak and communicate at the highest possible level. That really is a crucial element. Obviously not everyone will end up being a literary master, but writing and speaking become really important skills when the students graduate.

Engineering made me a better poet and poetry made me a better engineer.

RB: I hope that's indeed changed because when I went to school you took technical writing and that was about it. I don't think I wrote a complete sentence during the last three years of my engineering curriculum. So I certainly hope that's changed.

RL: I'll give you a little personal story. When I started my undergraduate career at Penn State, during my freshman orientation I met with a faculty member who was my academic advisor for the first year. After about half an hour of identifying classes to schedule, she looked me straight in the eye and said "You ought to see a speech pathologist!" That was one of the best pieces of advice I ever got. I grew up in northeast Pennsylvania where the dialect was remarkably strange and I never recognized it until I got to Penn State and she pointed this out to me. I saw a speech pathologist for half an hour a week for the first semester; she would record our conversation and play it back, and that was an enormous help to me.

One other little question, about electronic communication. Do you find iPhones and iPads and all the electronic communications to be an asset to you or a nuisance? I'm just curious about how someone who's a writer looks at all that.

RB: I think obviously it has its benefit and its detriment. Especially now that I'm traveling a lot it's really nice to be able to be mobile and have my email on my phone. Of course, I grew up before the advent of PCs at home. Even in engineering, when I started working full time, we were just starting the conversion to certain electronic media. I've found, honestly, that on the job it's become a bit of a nuisance, especially with plans and drawings; everybody holds on to old drawing files—it's ridiculous, because the free amount of storage and memory space is just endless, whereas I remember when there was only one drawing file and that was it. Now you spend a good percent of your time just keeping track of drawings and communications. Technology has helped the consulting engineer tremendously, but it's also sort of bogged down because you have 50 people emailing you about the same thing and there's a responsibility to communicate with people constantly about a project.

Cameron Fletcher: I'm curious about your comments about the intersection and mutual influence between poetry and engineering. Of course that's increasingly true in the sciences and engineering as well, but usually not across such different disciplines and areas. Are there areas other than poetry in your life influenced by your engineering, other activities or interests?

The lines of a poem are like trusses in a bridge: one line carries the weight from the line above it and transfers it to the next.

RB: First, I want to clarify that there's engineering as a career and there's the engineering mind. I think that as careers there's probably not much intersection even though I call myself a PE, a poet engineer. But I do think my education, my discipline, my engineering mind has become a great problem solver, and I apply that to every part of my life—to creating my household budget, doing spreadsheets to figure out optimal times to change the cat litter.... I apply that rigorous sort of problem-solving skill to everything.

The training of the mind that engineering brings is amazing when it comes to logic and looking at patterns, and I think that's part of how it influences my poetry. I approach a poem almost as a proof, a problem: here I have this undefined mass of emotion, what are the pieces of this and how do I write a poem around it? What's the first line? What's the second line? The lines of the poem are almost like trusses in a bridge: one line carries the weight from the line above it and transfers it to the next line. I always think of that sort of rigorous logic in everything, even in poetry. I approach my life that way and sometimes I have to remember to let go and just leave things up to chance a bit. But as you know, when an engineer leaves something up to chance, people die. So it's ingrained in me to not leave things up to chance.

RL: Along those lines, you mentioned in the *Globe* interview that Sam Florman's book *The Existential Pleasures of Engineering* (1976, 2nd ed. 1994) made quite an impression on you. What about his book caught your attention?

RB: I realized that historically engineers were multifaceted individuals, whereas education has changed so that now you specialize in one thing and don't do anything else. Earlier on, engineers were much more gregarious and well-rounded characters because they were convincing people to build crazy things like the Golden Gate Bridge and the Brooklyn Bridge. Engineers were more social animals than I had been led to believe, and reading that perspective on engineering gave me permission to say "I can be an engineer and do all sorts of different, crazy stuff as well. I'm a whole person. Engineering is one thing but it doesn't mean I can't do other things." Reading Florman's book gave me permission to explore my creative curiosities on other fronts and be a unique individual; I realized that the stereotype of engineers wasn't really true, it was just what we had come to expect from ourselves and from others. Engineers are humans.

If you look at some historical figures who have really distinguished themselves, you often learn that they had multiple interests and careers. Joseph Strauss was the chief structural engineer on the Golden Gate Bridge and a poet. Alfred Hitchcock studied electrical engineering. It's that synthesis of knowledge that makes the strength in whatever you choose.

RL: You said that engineers are social animals. I agree. When you think about engineering systems, they should serve societal purposes. From that perspective I think that civil engineers in particular, in my experience, have a much deeper sense of the social value of what they do, that the connection between serving people, serving society, and what a person does seems to be much clearer in civil engineering than perhaps other fields. Do you see that?

RB: I certainly think so. In my work with communities over the past 8 to 10 years, sometimes it took longer to get a cohesive vision with the community than it did to design and build the project. What it taught me, and what I used to tell my engineers, is “Look, this is not just a sidewalk, this is not just a retaining wall in a park. There is a physical landscape, a hardscape, but there’s also an emotional landscape that overlays all of it. This is for people: people are going to use this. People are going to walk on this sidewalk. People are going to sit on these benches. People are going to enjoy this park.” It is connected to people and to history. You can’t come into a town and say “Well, you should really have 20-foot sidewalks and blah blah blah….” People have ownership and it’s about what they want guided through your professional experience and what works and what doesn’t work, but at the same time there is an emotional attachment to their towns. It’s the idea of service.

CF: You mentioned students. Do you have other forums for outreach to engineers and people in the world of poetry? Do you see yourself as a communicator and contributor in both areas to people in different communities, whether it’s teaching or lecturing or reaching out to students at the college or high school level?

RB: I’m on the road about 70 percent of my days now. That is my outreach. In all my readings and lectures, especially at universities and high schools, I try to emphasize the idea of being a well-rounded person and of taking a liberal arts approach to life even if you don’t have a liberal arts degree. I explain that if you think you can escape from writing through engineering or biology, guess again. I say the same things to the artists in the room, too: Don’t dismiss other interests and other things that you don’t think are part of the art world, because inspiration comes from any place and everything you learn at some point is used in some way. So I advocate for that kind of approach to life.

And I think artists stereotype themselves too. Recently, I was the commencement speaker for an arts college and I expressed to the graduates that they don’t have to be the starving artist; having other interests or jobs to support their art doesn’t make them sellouts. I’ve also been the keynote speaker at the Northeast Association of Transportation Engineers and a few engineering firms; I have some engineering poems, as I like to call them, which I share with them. I sign and seal my books with my embossed engineering seal (I don’t know if I’m going to get in trouble with the board for that!).

I always emphasize the idea of being a well-rounded person, of taking a liberal arts approach to life even if you don’t have a liberal arts degree.

Sometimes people confess to me in these conferences, “I’ve been writing for a long time but I haven’t shown anybody.” They’re really hesitant. I explain that you’re free to explore your creative curiosity, and that will only make you a better person, and if you’re a better person you’re a better engineer. If you’re more dynamic and understand yourself and the world around you, you’re going to be a better anything. I try to be consistent with that message. It’s ironic because our education system is running scared because of the economy and we keep specializing and specializing and thinking “STEM, STEM, STEM!”[2] But I think, “No, you need to be more dynamic and more creative when the economy is down. Your success as an engineer depends on a lot more than Calculus 5.” I think people understand that message when they hear it, and feel bolstered to act on it.

CF: I think in this country more than in others we do tend to be more monofocal and monodimensional.

RB: I think there’s a cultural element to that. Even linguistically, the word in Spanish for *engineer*, *ingeniero*, comes from *genius*, from *genio*, and in English the word *engineer* comes from *engine*, giving the idea that we’re just kind of a machine, stamping out the same thing over and over again. The truth is we’re some of the most

[2] STEM = science, technology, engineering, and mathematics

interesting, most intelligent, most dynamic, most curious people in the world. But we get trapped in boxes and start believing and living the stereotypes. But history has shown us to be pretty dynamic if we look at a list of the people who have been engineers and have done amazing things outside of their field. Look at Florman himself—what an amazing, dynamic person.

RL: Are engineering schools on your itinerary in general now?

RB: Not as much as you would think. It depends on invitations. At about 10 percent of the readings the engineering department or some engineers, geologists, and biologists are invited. But in general I think it's the importance of writing overall that's fundamental. The person who gets the grants from the NEA or the science foundations is the one who knows how to write about ideas. Writing is important no matter what you do.

RL: On that point, there's now talk about STEAM education—science, technology, engineering, art, and mathematics—and I think that's a good sign. It seems like it's taking its time getting launched but it looks like a good idea.

RB: Yes, the last thing we need to do is be less dynamic, less creative. It's the opposite: you've got to be more creative, especially in this generation of students. They are so used to so many pieces of information coming at them, so used to Facebook, Twitter, email—they don't know how to write in cursive anymore, it's not even being taught anymore. The point is to create an even more dynamic person through education. There is a sense that, "Okay, you're going to study engineering or biology and you will never read *Moby Dick*. You don't need any of that kind of engagement." I think it's a shame. Inspiration, ideas, and creativity come from connecting dots that you wouldn't ordinarily connect. That is by definition creativity, [and] creative problem solving.

CF: Is there anything you would like to convey to the *Bridge* readership, which includes the members of the National Academy of Engineering, Congress, engineering departments all over the country, libraries, and engineering schools.

RB: Writing and language are key to success for an engineer for many different reasons. Remember that everyone is a multidimensional, multifaceted human being, and that there's absolutely nothing queer or wrong if you're interested in painting and you've been a civil engineer for 20 years—that's absolutely wonderful. We don't necessarily have to change careers to enjoy and follow our creative curiosities and benefit from them in our own jobs.

On one of my last big projects, a city hall complex in the city of South Miami, I wrote a poem based on some old photographs of the street, Sunset Drive, where I was reimagining the whole streetscape. It has to do with our legacy as engineers and our place in the world and connection to the project. The mayor insisted that I read it at the groundbreaking ceremony. For the first time in my life, I got to read a poem in my hard hat!

RL: This has been a lot of fun, Richard, and we really appreciate your helping us launch this new element in *The Bridge*.

RB: I think it's a great idea, a wonderful idea. And you won't run out of people and stories, I'm sure. Once you start looking I'm sure you'll find people coming out of all sorts of creative closets.

Photo of a Man on Sunset Drive circa 1914 and 2008

Groundbreaking Ceremony, Sunset Drive Improvements. Project No 1929-26

by Richard Blanco, P.E.

And so it began: the earth torn, split open
by a dirt road cutting through palmettos
and wild tamarind trees defending the land
against the sun. Next to the road, a shack
leans into the wind, on the wooden porch,
white chickens peck at the floor boards
beside crates of avocados and key limes,
a man under the shadow of his hat, stares
into the camera. It is 1914. He doesn't know
that in a lifetime the unclaimed land behind
him will be cleared of scrub and sawgrass,
the soil will be turned, made to give back
what the farmers wish, their lonely houses
will stand acres apart from one another,
jailed behind the boughs of their orchards.
He'll never buy sugar at the grocery store,
mail love letters at the post office, or take
a train at the depot of the town that will rise
out of hundred-million years of coral rock
on promises of paradise. He'll never ride
a new Model-T puttering down the dirt road
that will be paved over and stretch farther,
farther west into the horizon, reaching for
the setting sun after which it will be named.
He can't even begin to imagine the shadows
of buildings rising taller than the palm trees,
the street lights glowing like counterfeit stars
dotting the sky above the road, the thousands
that will take the road every day, that will also
call this place home less than a hundred years
after the photograph of him that hangs today
in City Hall as testament. He'll never meet me,
the engineer hired to transform the road again,
to bring back the tree shadows and birdsongs,
to build another promise of another paradise
that will last another forever. He will never
see me, the poet standing before him, trying
to read his mind across time, wondering if
he was thinking what I'm thinking today
as I look at him looking down the same road
that will live on for years after I vanish too.

NAE News and Notes

NAE Newsmakers

Daniel Berg, Distinguished Research Professor of Engineering, University of Miami, received the prestigious **Siwei Cheng Award in Information Technology and Quantitative Management** at the 2nd annual meeting of the International Academy of Informational Technology and Quantitative Management (IAITQM) in Moscow, June 3–5. The award was given to Dr. Berg as "a person who devoted genius efforts to applying quantitative methods and information technology to solve management problems." The award is in honor of Siwei Cheng, a former leader in the Chinese Congress and currently the head of a major program on economic theory at the Chinese Academy of Sciences. IAITQM, with founding members from over 50 countries, was established in 2011 to promote innovative excellence in information technology and quantitative management.

The IEEE Information Theory Society has named **A. Robert Calderbank**, professor, Duke University, the 2015 recipient of the **Claude E. Shannon Award**, which honors "consistent and profound contributions to the field of information theory." It is the most prestigious prize in information theory, covering technical contributions at the intersection of mathematics, communication engineering, and theoretical computer science.

Nancy D. Fitzroy, GE Corporate Research and Development, was awarded Rensselaer Polytechnic Institute's (RPI) top honor, the **Davies Medal for Engineering Achievement**, presented on May 5. The first female recipient of the prestigious award, Dr. Fitzroy has authored 100 technical papers, holds three patents, and was one of the first female helicopter pilots. She became an Honorary Fellow of the UK Institution of Mechanical Engineers in 1988. "Nancy Fitzroy is a world-class engineer, a pioneer, and a spirited leader," said RPI President Shirley A. Jackson. "Her technical contributions have been fundamental to a range of technologies."

Tau Beta Pi, the engineering honor society, has named two NAE members as 2014 winners of its **Distinguished Alumnus Award**: **Delon Hampton**, chairman of the board, Delon Hampton & Associates, and **Asad M. Madni,** retired president, chief operating officer, and CTO, BEI Technologies, and independent consultant. The award recognizes alumni who have demonstrated adherence to the Tau Beta Pi ideals—integrity, breadth of interest, adaptability, and unselfish activity—and to fostering a spirit of liberal culture on local, national, and international scales.

Paul G. Kaminski, chairman and CEO, Technovation Inc., recently received two prestigious awards. AIAA, the largest aerospace professional society in the world, named him an **Honorary Fellow**, the highest distinction conferred by AIAA. It is granted to "preeminent individuals who have long and highly contributory careers in aerospace and who embody the highest possible standards in aeronautics and astronautics." AIAA honored Paul at its annual gala, held in Washington, DC, on April 30. He also received the **Leatherneck Award** at the Marine Corps Scholarship Ball in the New York City Hilton Hotel on May 2. The Marines recognized him for his career accomplishments and efforts in raising scholarship funds for youth (with a focus on children of Marines wounded or killed in action) so they will be able to keep the country economically and militarily strong when the torch is passed to them.

The Chemical Heritage Foundation (CHF) and the Biotechnology Industry Organization (BIO) selected **Robert S. Langer**, David H. Koch Institute Professor, Massachusetts Institute of Technology, to receive the **2014 Biotechnology Heritage Award**, presented during the 2014 BIO International Convention, June 23–26 in San Diego. The award honors individuals who have contributed significantly to the growth of biotechnology through discovery, innovation, commercialization, and/or public understanding. "Bob Langer is the founder of tissue engineering in regenerative medicine as well as creator of many transdermal and controlled drug delivery systems," said Carsten Reinhardt, CHF's president and CEO. "During his amazing career he has published more than 1,200 articles, which have been cited nearly 150,000 times, more than any other engineer. Bob is truly one of the great biotechnology pioneers." Dr. Langer also has been named a **2014**

Kyoto Prize Laureate for his work in the fields of biotechnology and medical technology and for "creation of tissue engineering and drug delivery system technologies." The award—a diploma, the Kyoto Prize Medal, and ¥50 million—will be presented by the Inamori Foundation on November 10, 2014, in Kyoto. The international prize honors those who have contributed significantly to the scientific, cultural, and spiritual betterment of humankind, and is presented annually in each of the following three categories: advanced technology, basic sciences, and arts and philosophy.

Richard K. Miller, president, Olin College of Engineering, received a **2014 Distinguished Alumni Award** from the California Institute of Technology, the highest honor the institute bestows on its alumni. He was cited for "visionary leadership and commitment to innovation in engineering education for the benefit of society. As the founding president of Olin College, Miller led the creation of a new institution recognized for its unique teaching methods and models."

Sanjit K. Mitra, research professor of electrical engineering, University of California, Santa Barbara, and Stephen and Etta Vara Professor Emeritus, University of Southern California, Los Angeles, has been elected an **International Member of the Croatian Academy of Engineering** in the Department of Information Systems.

Yannis C. Yortsos, dean, University of Southern California Viterbi School of Engineering, was formally inducted into the **Academy of Athens** in Greece for his exceptional leadership and accomplishments in the field of engineering. He was honored for his contributions to fluid flow, transport, and reaction processes in porous and fractured media as well as his extensive work with technical publications and his dedication to engineering education and research. "Having grown up in Greece, it's a great honor to be elected an associate member of the Academy of Athens, which traces its roots to the ancient academy founded by Plato," Dr. Yortsos said.

Bernard M. Gordon Prize for Innovation in Engineering and Technology Education

On Friday, May 2, 2014, the NAE presented the 2014 Bernard M. Gordon Prize for Innovation in Engineering and Technology Education to the Thayer School of Engineering at Dartmouth College. The winners were Dr. John P. Collier, Myron Tribus Professor of Engineering Innovation; Dr. Robert J. Graves, John H. Krehbiel Sr. Professor of Emerging Technologies and director of the master's in engineering management program; Dr. Joseph J. Helble, dean and professor of engineering; and Charles E. Hutchinson, dean emeritus of the Thayer School. The recipients accepted their awards with NAE President Dr. **C. D. Mote, Jr.** at the podium. Also assisting in the presentation were Mr. **Bernard M. Gordon**, BMG Charitable Trust, and Dr. Philip J. Hanlon, President, Dartmouth College. The presentation concluded with remarks from Dr. Hanlon.

Acceptance Remarks by Joseph J. Helble

Left to right: Dr. C. D. (Dan) Mote, Jr., Dr. Charles E. Hutchinson, Dr. Joseph J. Helble, Dr. Robert J. Graves, Dr. John P. Collier, Mr. Bernard M. Gordon, and Dr. Philip J. Hanlon.

On behalf of my colleagues who join me here on the stage, I am deeply honored to accept this award for Dartmouth College and the Thayer School of Engineering.

Our sincere appreciation goes to NAE President Dr. **Dan Mote**, NAE Executive Director Dr. **Lance Davis**, Ms. Deborah Young from NAE, Mr. and Mrs. Bernard Gordon for making this award possible, and members of the Gordon Prize Selection Committee, represented today by Olof Johnson and **Nicholas Donofrio**, for traveling to Hanover to present and celebrate the Bernard M. Gordon Prize. The award was established in 2002, and is being presented at the recipient institution for the very first time. We are privileged to have this opportunity to host you.

In recognition of the significance of this award to Dartmouth and the Thayer School of Engineering, we are also honored to be joined by Dartmouth President Philip Hanlon, several members of the Thayer School Board of Overseers, members of the Engineering Management Corporate Collaborative Council, our families and friends, and the greater Dartmouth Engineering alumni community, many of whom are joining us via live streaming of this event.

In particular I need to thank our students and alumni—the Thayer School of Engineering would not be what it is without your boundless energy, limitless intellectual curiosity, and willingness to tackle whatever the faculty throws at you—as true today as it was 50 years ago, when our school, and our curriculum, began to take its current form.

About five years ago I took a look at engineering course catalogues from several major research universities, both public and private, comparing their engineering programs from the present, from the 1980s when I was a student, and from the 1950s. Little had changed. There was virtually no interaction between engineering departments at the undergraduate curricular level—no opportunity, for example, for mechanical engineering and electrical engineering students to take the same electives, or work together on integrated project teams. True collaboration with business schools to help teach skills associated with technology entrepreneurship were limited, and PhD programs remained structured the way they had been for nearly a century. The departmental silos for which academic institutions are frequently criticized were very real.

The Bernard M. Gordon Prize has, over the past 14 years, recognized institutions and programs that have taken significant steps to break this mold, to engage students to cross disciplinary boundaries, to take steps to prepare them to become engineering leaders. At Dartmouth, where our faculty have long been as dedicated to our teaching as to our original scholarship, we are deeply honored to be recognized in their company.

This award celebrates our problem-based focus in undergraduate engineering education, beginning with the required first course in Engineering Problem Solving, ENGS 21, whose simple title, "Introduction to Engineering," seems to say little, yet at the same time—introduction to *engineering*—speaks volumes about the creativity, innovation, and entrepreneurial opportunity that represent the best of what engineering can be. It celebrates our strong partnership with our business colleagues in our Master's of Engineering Management Program, where students gain understanding of the business elements of assessing and developing technology. And it recognizes our experiment in PhD education, the creation of our PhD Innovation Program in 2008, a program that challenges some of our PhD students not to rely on others but to apply their scholarship directly, to put their work to immediate use and to benefit the greater good by becoming technology entrepreneurs.

These programs are the pillars of the Dartmouth Engineering Entrepreneurship Program, a comprehensive effort to teach engineering students that they have an opportunity through their work to have an immediate and measurable impact. They provide us the opportunity to teach our students—and remind ourselves—that as engineers we have made a commitment to use science, and here at Dartmouth our liberal arts education, to *understand* the world, and then to use engineering to *change* it.

On behalf of my co-recipients John Collier, Charles Hutchinson, Robert Graves, and all who contribute to these efforts, I thank you for this award.

EngineerGirl Announces 2014 Essay Contest Winners

The National Academy of Engineering announced the winners of its 2014 *EngineerGirl* essay contest. In recognition of the NAE's 50th anniversary this year, students in grades 3–12 were asked to describe how engineering has addressed societal needs in the past 50 years and to suggest ways that it will impact society in the next 50 years in one of the following areas: nutrition, health, communication, education, and transportation. Prizes were awarded to students in three categories based on grade level.

"This year's essay competition supports beautifully the 50th anniversary celebration of the NAE. The contestants present their ideas for the most important impacts of engineering on our lives they expect over the next half century," said NAE President **C. D. Mote, Jr.** "It is inspiring to see young people be so passionate about engineering, and dreaming about a future that they will create."

Cora Oldfield, a fifth-grader from Amherst, NY, placed first among third- to fifth-grade students for her essay on engineering efforts toward preventing and treating malaria. Eighth-grader Ruth Hammond from H.H. Poole Middle School in Stafford, VA, won first place among entries from grades 6–8 for her explanation of the wide-ranging roles engineers play in the field of nutrition. Among 9th to 12th graders, Isabella Lee, a sophomore at Illinois Math and Science Academy in Aurora, placed first for her essay about advances in surgical procedures that rely on engineering.

2014 Japan-America Frontiers of Engineering Symposium Held in Tokyo

Hiroko Terasawa (Tsukuba University) and Jeffrey Urban (Lawrence Berkeley National Lab) discuss her poster during the poster session.

The 2014 Japan-American Frontiers of Engineering Symposium (JAFOE) was held June 9–11 at the National Museum of Emerging Science and Innovation (Miraikan) in Odaiba, Tokyo. The Engineering Academy of Japan is NAE's partner in this endeavor. NAE member **Steven DenBaars**, professor of materials and codirector of the Solid-State Lighting Center at the University of California, Santa Barbara, and Yoshikazu Nakajima, associate professor of bioengineering and mechanical engineering at the University of Tokyo, cochaired the symposium.

Approximately 60 earlier-career engineers from US and Japanese universities, companies, and government labs attended the 2014 JAFOE symposium to discuss leading-edge developments in four engineering fields: bioimaging, energy harvesting and power transmission, noise control engineering in healthcare environments, and field robotics for disaster response.

Bioimaging, a field where physics and engineering intersect with biology and medicine, occurs at multiple scales, from a few angstroms (DNA) to meters (whole body). To visualize at these distinct scales, different imaging techniques are employed. Single-molecule fluorescence imaging can be used for analyzing the dynamics of a single protein molecule, while positron emission tomography can trace cancer cells throughout the body. The speakers in this session focused on two areas: (1) molecular imaging, where talks covered imaging and mathematical modeling of molecular activities in living cells and new technologies for molecular imaging of the brain, and (2) endoscopic imaging, where speakers described optical nanoscale imaging as well as the advanced imaging technologies of narrow-band imaging, autofluorescence imaging, infrared imaging, and endocytoscopy systems.

The Power Unplugged session focused on the generation and transmission of power for buildings, vehicles, biomedical devices, and personal electronics through energy harvesting and wireless power transmission—in other words, without needing to plug in to the electrical grid. Energy-harvesting devices such as thermoelectrics and piezoelectrics capture untapped thermal and mechanical energy from the ambient environment and convert it into useful energy. Talks here described research in nanomaterials and nanoelectronics for energy harvesting and a low-cost and environmentally friendly sensing system enabled by inkjet printing of conductive material for ambient radiofrequency-energy harvesting. Wireless power involves the use of antennas to scavenge ambient unused electromagnetic power and use it to power electronics. Presenters described research in wireless power transfer technologies via radio waves and radiative cooling, which allows passive cooling of a structure through radiation.

The next session highlighted the frontiers of noise control research and technology, specifically in healthcare environments. The first speaker laid the foundation by describing, first, how acoustics factors into the human experience of sound from sources such as transportation systems and power facilities, and then advances in wave theory–based models for the prediction and assessment of environmental noise.

The next two speakers discussed noise control engineering in health-care environments where excess noise from patient and staff activity, medical equipment, and medical alarms can impede patient healing and recovery and contribute to the risk of medical errors and alarm fatigue. The session concluded with a talk on brain wave sonification, a technique that utilizes acoustics to improve the understanding of biological information.

The symposium concluded with presentations on field robotics—the use of robotic technologies in uncontrolled environments associated with disaster response, construction, forestry, agriculture, mining, subsea, defense, and space. Given recent high-profile events such as the 2011 East Japan earthquake and tsunami and the ensuing damage to the Fukushima Daiichi Nuclear Power Station as well as the *Deepwater Horizon* oil spill, the presenters focused on field robotics for disaster response and the role robotics can play in mitigating crisis situations. Speakers described Quince, a monitoring robot that was used at the Fukushima Daiichi power facility; resource-constrained autonomous aerial systems and how they may cooperate with teams of heterogeneous robots; unmanned construction systems to mitigate debris flow damages after volcanic eruptions; and the DARPA Robotics Challenge, a competition to develop hardware and software that will support human-robot collaboration in performing hazardous activities in disaster zones.

The dinner speech was given by Dr. Tomoko Nakanishi, a professor in the Graduate School of Agricultural and Life Sciences at the University of Tokyo and a commissioner with the Japan Atomic Energy Commission. She spoke about real-time imaging in plants, radiation measurement, and agricultural implications of the Fukushima nuclear accident.

Other highlights included a poster session on the first afternoon for participants to describe their technical work or research and a visit to Tokyo University of Marine Science and Technology that included a tour of the Centennial Museum there and a look at "RAICHO," a new type of plug-in electric boat. Attendees enjoyed a *kaiseki* meal, or traditional Japanese multicourse dinner, on the last evening.

Funding for this activity was provided by The Grainger Foundation, Japan Science and Technology Agency, US National Science Foundation, and Lawrence S. Finegold and the Michiko So Finegold Memorial Trust. The next JAFOE symposium will be held in 2016 in the United States.

The NAE has been holding Frontiers of Engineering symposia since 1995. For more information about this meeting and the symposium series, visit www.naefrontiers.org. To nominate an outstanding engineer to participate in future Frontiers meetings, contact Janet Hunziker at jhunziker@nae.edu.

Fifth Indo-American Frontiers of Engineering Held in Mysore

On March 19–21 the fifth Indo-American Frontiers of Engineering Symposium (IAFOE) was held at the Infosys Global Education Center in Mysore, India. NAE foreign member **N.R. Narayana Murthy**, founder and chairman emeritus of Infosys Ltd., graciously agreed to host the meeting at Infosys' beautiful training campus about 90 miles from Bangalore.

The IAFOE symposium is held biennially and is one of six international FOE meetings. The Indo-US Science and Technology Forum (IUSSTF) is NAE's partner in this endeavor. NAE member **Lisa Alvarez-Cohen**, Fred and Claire Sauer Professor of Civil and Environmental Engineering at the University of California, Berkeley, served as US cochair; Upadrasta Ramamurty, professor of materials engineering at the Indian Institute of Science in Bangalore, was cochair for the Indian side.

Typical of the design of the bilateral FOEs, this meeting brought together approximately 60 engineers, ages 30–45, from US and Indian universities, companies, and government labs for a 2½-day meeting, where leading-edge developments in four engineering fields were discussed. The session topics were green approaches to communications, water resources management in the face of climate change, engineering in the context of big data, and biomaterials. Each session included presentations by two Indian and two US speakers.

The first session was Green Approaches to Communications. Communication networks account for a growing proportion of data traffic around the world; however, sustainability challenges from energy efficiency to recycling threaten the growth, improvement, and proliferation of communication devices and systems. Green communications is an active research area exploring new technologies that advance the sustainable and cost-effective design of advanced communication networks. Talks in this session focused on mobile processor architectures, specifically design implications and challenges for energy efficiency; energy efficiency in cellular networks; challenges and opportunities in mobile software power management; and energy harvesting–based green wireless communication systems.

Speakers in the session on Water Resources Management in the Face of Climate Change noted that as climate change continues to alter the fundamental elements of the hydrological cycle, the human and natural systems that depend on or are influenced by water resources infrastructure will be forced to adjust. The presenters explored four areas critical to the future of the world's water resources systems in the con-

Fifth Indo-American Frontiers of Engineering text of climate change: (1) causes of climate change and the increased prevalence of extreme hydrologic events; (2) emerging water resources modeling technologies to understand climate change impacts and develop adaptation strategies; (3) the developing field of eco-engineering and how these methods are being applied to increase the resilience of water resources systems; and (4) implementation of smart water resources infrastructure that will improve the ability to adapt water resources systems to climate change and respond to extreme events such as floods and hurricanes.

Data collection—from genetic sequencing and health and environmental monitoring to information communicated through social networks—is ubiquitous in today's world. It is hoped that new knowledge can be gained from these massive amounts of data to enhance climate prediction, optimization of manufacturing processes, or management and control of complex systems such as the energy grid, transportation, communication networks, and water resources. In the session on Engineering in the Context of Big Data speakers described the Internet of Manufacturing Things (a take on the term "the Internet of Things"), which focused on how shop-floor data can be collected, stored, and analyzed to improve manufacturing capabilities; predictive analytics for industrial applications; the impact of big data on drug discovery; and how knowledge discovery from large volumes of data generated by space exploration can be facilitated by prioritizing observations that are most likely to inspire new discoveries.

Biomaterials are derived from or designed to mimic a naturally occurring substance. The speakers in this session addressed some of the challenges in this field in the context of drug design and medical technology. Presentations covered current research on the delivery of molecules to precise locations for sustained purposes, incorporation of self-assembled and stimuli-responsive systems into drug delivery systems, and identification of peptides that target cancer cells and overcome obstacles in cancer drug delivery. The session concluded with a talk on how to translate disruptive biomaterial technologies into novel therapeutic applications and the challenges in bringing biomaterial research to commercialization.

Dr. Baldev Raj, president of the Indian National Academy of Engineering, gave a dinner speech the first evening, *A Perspective on Technological Challenges in India*. He focused on the challenges of energy security and sustainability and noted the importance of developing a portfolio of energy solutions and technologies as well as the need to develop the human resources to achieve development goals. As former director of the Indira Gandhi Center for Atomic Research, he also provided his perspective on the history and challenges of nuclear power development.

A poster session on the first afternoon provided an opportunity for all the participants to talk about their research or technical work. On the second afternoon, the group made a return visit to Mysore Palace, the official residence of the former royal family of Mysore, after seeing it illuminated on the evening before the symposium started. The guided tour was followed by dinner at the Lalit Mahal Palace, the second largest palace in Mysore.

Primary support for this meeting was provided by the IUSSTF and Infosys. Additional support was provided by Lockheed Martin. The next Indo-American Frontiers of Engineering Symposium will be held in 2016 in the United States.

NAE has held Frontiers of Engineering symposia since 1995. For more information about this meeting and the symposium series, visit www.naefrontiers.org. To nominate an outstanding engineer to participate in future Frontiers meetings, contact Janet Hunziker at jhunziker@nae.edu.

NAE Center for Engineering, Ethics, and Society Releases Videos on Climate Change

At the national meeting on "Climate Change and America's Infrastructure: Engineering, Social, and Policy Challenges" in January 2013, leaders in climate adaptation, city management, engineering systems, public engagement, and other key fields gathered to consider the wide-ranging implications of climate change. The NAE Center for Engineering, Ethics, and Society (CEES) produced two videos from interviews conducted at the workshop. Titled "Climate and Infrastructure I: Why Does It Matter?" and "Climate and Infrastructure II: Who Should Address It?," the videos highlight participant views about the impacts and importance of addressing climate change and the various types of expertise that will be needed to adequately address stresses to engineering systems. Both videos are designed to serve as a starting point for discussion and enable educators and others to inform engineers and the public about the numerous challenges posed by climate change. The videos can be viewed at onlineethics.org.

CEES collaborated in 2010–2014 with Arizona State University, the Museum of Science Boston, the University of Virginia, and the Colorado School of Mines to develop a Phase I Climate Change Education Partnership (CCEP). The partnership, focused thematically on the impacts of climate change for engineered systems, aims to catalyze educational efforts to prepare current and future engineers, policymakers, and the public to meet these challenges.

This work was supported by Grant No. 1043289 between the National Academy of Engineering and the National Science Foundation. Any opinions, findings, conclusions, or recommendations expressed in the videos are those of the speakers and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

Commonweal/National Academies Interns Join NAE Program Office

Abby Estabillo

Marthe Folivi

Tina Tran

ABBY ESTABILLO, a fourth-year intern of the Commonweal/National Academies Internship Program, recently graduated from Montgomery College with her associate's degree in science with a focus in electrical engineering. During her 10-week internship this summer she worked with the NAE Program Office and aided in the development of NAE's *EngineerGirl* website, answering and forwarding students' questions to engineers. Under the supervision of Catherine Didion, Abby also incorporated edits to NAE prepublication reports. She will attend the University of Maryland in the fall to pursue her bachelor's degree in electrical engineering at the Clark School of Engineering.

MARTHE FOLIVI is a second-year Commonweal and National Academies intern. She is a rising sophomore at Ripon College in Wisconsin, where she is pursuing a BS in chemistry and biology and a BA in Spanish and French. Last year she worked with the marketing department of the National Academies Press, helping with foreign contracts and the Next Generation Science Standards book, among other things. This year she worked with Greg Pearson on the NAE Engineering Technology Education study. Marthe has interests in organic chemistry, biochemistry, pathology, and molecular biology and hopes to combine these disciplines to develop a method for regeneration in organisms that have lost limbs. After college she plans to attend medical school as part of an MD-PhD program and wants to specialize in emergency medicine for her MD. At school she is a student senator, a resident assistant, and works in the chemistry department. This summer she learned a lot about the field of engineering and its importance to her medical interests. She hopes to apply what she has learned to her studies next year and the research project she will complete to gain her degrees.

TINA TRAN is a rising junior at Towson University in Maryland, where she is majoring in chemistry and plans to pursue a career in the pharmaceutical field (she decided to go to pharmacy school to pursue her interest in medicine without having to encounter blood). Tina immigrated to the United States from Viet Nam in 2008 at the age of 15 and started as a ninth grader at John F. Kennedy High School in Silver Spring, Maryland. This is her third year as an Anderson & Commonweal intern and her second year at the National Academies. She worked with the Water Science and Technology Board of the Division of Earth and Life Studies last summer. This year she worked in the NAE, under Catherine Didion's supervision, on the reorganization and migration of the website of the Committee on Women in Science, Engineering, and Medicine. She is a math tutor for the Academic Achievement Center at Towson and a volunteer with the Viet Nam Medical Assistant Program, a nonprofit organization that helps Montgomery County (Maryland) residents in screening, management, awareness, and solutions in hepatitis B.

Calendar of Meetings and Events

September 19	Roundtable on Science, Technology, and Peacebuilding Summit on Engineering Durable Peace
September 26–27	NAE Council Meeting
September 27	NAE Peer Committee Meetings
September 28–29	NAE Annual Meeting
September 30	AIAA Inaugural Yvonne C. Brill Lecture
October 26–29	Frontiers of Engineering Education Irvine, California
October 28–29	Online Ethics Center Expansion Meeting
November 3–5	Guiding Implementation of K–12 West Coast Stakeholders Meeting Pasadena
November 10–12	EU-US Frontiers of Engineering Seattle
November 19–21	NAE Engineering Education Workforce Continuum Committee Meeting and Workshop
December 2–3	Committee on Engineering Technology Education Meeting
December 5–6	2015 Election Committee on Membership Meeting Irvine, California

All meetings are held in National Academies facilities in Washington, DC, unless otherwise noted.

In Memoriam

ARTHUR P. ADAMSON, 95, retired manager, advanced commercial engine programs, GE Aircraft Engines, died on May 3, 2014. Mr. Adamson was elected to the NAE in 1980 for creativity, inventiveness, and engineering in the design and development of aircraft gas turbine and other engineering apparatus.

LEO C.M. DE MAEYER, 86, director emeritus, Department of Experimental Methods, Max Planck Institute for Biophysical Chemistry, died on June 18, 2014. Dr. de Maeyer was elected a foreign member of the NAE in 1998 for the development of innovative experimental methods and instrumentation for investigating molecular mechanisms of faster chemical reactions.

ALEXANDER H. FLAX, 93, consultant, died on June 30, 2014. Dr. Flax was elected to the NAE in 1967 for contributions to solid and fluid mechanics and aerodynamics.

CARL W. HALL, 89, president and PE, Engineering Information Services, died on April 18, 2014. Dr. Hall was elected to the NAE in 1989 for fundamental research in agricultural product processing and food engineering.

GEORGE H. HEILMEIER, 77, retired chairman, Telcordia Technologies, Inc., died on April 21, 2014. Dr. Heilmeier was elected to the NAE in 1979 for contributions to liquid crystal technology.

IVAN P. KAMINOW, 83, adjunct professor, University of California, Berkeley, died on December 18, 2013. Dr. Kaminow was elected to the NAE in 1984 for basic contributions to optical telecommunications in the areas of electro-optic modulation, integrated optics, optical fibers, and semiconductor lasers.

STEPHANIE L. KWOLEK, 90, retired research associate, fibers pioneering research laboratory, E.I. du Pont de Nemours & Company, died on June 18, 2014. Dr. Kwolek was elected to the NAE in 2001 for contributions to the discovery, development, and liquid-crystal processing of high-performance aramid fibers.

JAMES E. MCGRATH, 79, University Distinguished Professor, chemistry, adjunct professor of chemical engineering, Virginia Polytechnic Institute and State University, died on May 18, 2014. Dr. McGrath was elected to the NAE in 1994 for integration of synthesis with the performance and applications of polymeric materials and their composites.

LAWRENCE T. PAPAY, 77, retired sector vice president for integrated solutions, Science Applications International Corporation, CEO and principal, PQR, LLC, died July 28, 2014. Dr. Papay was elected to the NAE in 1987 for outstanding leadership in pioneering the research, development, and commercialization of electric power generation utilizing alternative and renewable technologies.

G. RUSSELL SUTHERLAND, 90, retired vice president, engineering and technology, Deere & Company, died on June 11, 2014. Mr. Sutherland was elected to the NAE in 1984 for outstanding contributions to agricultural mechanization resulting in humankind's assurance of food and fiber to the end of this century.

Publications of Interest

The following reports have been published recently by the National Academy of Engineering or the National Research Council (NRC). Unless otherwise noted, all publications are for sale (prepaid) from the National Academies Press (NAP), 500 Fifth Street NW–Keck 360, Washington, DC 20001. For more information or to place an order, contact NAP online at <*www.nap.edu*> or by phone at (800) 624-6242. *(Note: Prices quoted are subject to change without notice. There is a 10 percent discount for online orders when you sign up for a MyNAP account. Add $6.50 for shipping and handling for the first book and $1.50 for each additional book. Add applicable sales tax or GST if you live in CA, CT, DC, FL, MD, NC, NY, PA, VA, WI, or Canada.)*

Emerging and Readily Available Technologies and National Security: A Framework for Addressing Ethical, Legal, and Societal Issues. An NRC-NAE study considered ethical, legal, and societal issues relating to research on, development of, and use of rapidly changing technologies with low barriers of entry that have potential military application (e.g., information technologies, synthetic biology, and nanotechnology) as well as robotics and autonomous systems, prosthetics and human enhancement, and cyberweapons. This report addresses the ethics of using autonomous weapons that may be available in the future; the propriety of enhancing soldiers' physical or cognitive capabilities with drugs, implants, or prosthetics; and what limits, if any, should be placed on the nature and extent of economic damage that cyberweapons can cause. The report explores the conduct of research, research applications, and unanticipated, unforeseen, or inadvertent ethical, legal, and societal issues, and provides a framework for policymakers, institutions, and researchers to use in thinking about issues associated with these technologies of military relevance.

NAE members on the study committee were **William F. Ballhaus Jr.**, retired president and CEO, the Aerospace Corporation; **Jean-Lou A. Chameau**, president, King Abdullah University of Science and Technology; **Joel Moses**, Institute Professor, professor of computer science and engineering, and professor of engineering systems,

Massachusetts Institute of Technology; and **Alfred Z. Spector**, vice president, Research and Special Initiatives, Google Inc. Paper, $63.00.

Advancing Diversity in the US Industrial Science and Engineering Workforce: Summary of a Workshop. Thousands of gifted women and underrepresented minorities remain a disproportionally small fraction of those in science, technology, engineering, and math (STEM) careers, and industry, the largest employer category of those with STEM backgrounds, stands to benefit considerably from their greater inclusion. However, nothing short of a game-changing environment must be created to harness the talent of those not fully represented in the STEM workforce. This report, the summary of an NAE workshop held in May 2012 on the needs and challenges facing industry in particular, is intended to facilitate discussion and actions to address these complex issues. The workshop provided a forum for leaders from industry, academia, and professional associations to share best practices and innovative approaches to recruiting, retaining, and advancing women and underrepresented minorities in the scientific and engineering workforce throughout the nation's industries.

NAE members on the workshop committee were **Ann L. Lee** (cochair), senior vice president, Genentech Inc., and head of Global Technical Development, Roche; **Rodney C. Adkins**, senior vice president, IBM Corporate Strategy; and **Mauricio Futran**, vice president, Process Science and Advanced Analytics, Janssen Supply Chain, Johnson and Johnson. Paper, $42.00.

Science and Technology Capabilities of the Department of State: Letter Report. This interim report was written in response to a request from former Under Secretary Robert Hormats to assess the capabilities of the Department of State that are particularly important as science and technology become integral aspects of diplomacy.

NAE member **Glen T. Daigger**, senior vice president and chief technology officer, CH2M Hill, was a member of the study committee. Free PDF.

The Future of Advanced Nuclear Technologies: Interdisciplinary Research Team Summaries. The National Academies Keck Futures Initiative (NAKFI) Conference in 2013 focused on the Future of Advanced Nuclear Technologies to generate new ideas about how to move nuclear technology forward while making the world safer and more secure. Beyond the public's apprehension about the safety of nuclear power, which calls for better communication strategies, several challenges lie ahead for the nuclear enterprise in the United States. The workforce in nuclear technology is aging, there is an overreliance on large, high-risk reactor designs, and the supply of radioisotopes for nuclear medicine remains unstable—all problems crying out for solutions. This report summarizes 14 interdisciplinary research teams' collaborations on creative solutions to challenges designed to propel the policy, engineering, and social aspects of the nuclear enterprise forward.

NAE members on the steering committee were **Richard A. Meserve** (chair), president, Carnegie Institution for Science; **Albert Carnesale**, chancellor emeritus and professor, University of California, Los Angeles; **Michael L. Corradini**, professor, Department of Engineering Physics, University of Wisconsin-Madison; and **Warren Miller Jr.**, TEES Distinguished Research Professor, Texas A&M University System. Paper, $49.00.

Evaluation of the Implementation of WFIRST/AFTA in the Context of New Worlds. This report assesses whether the proposed Astrophysics Focused Telescope Assets (AFTA) design reference mission described in the 2013 report of the AFTA Science Definition Team is responsive to the overall strategy to pursue the science objectives of *New Worlds, New Horizons in Astronomy and Astrophysics* (NRC 2010), and in particular the survey's top ranked, large-scale, space-based priority, the Wide Field Infrared Survey Telescope (WFIRST). This report compares the WFIRST mission described in *New Worlds, New Horizons* to the WFIRST-2.4 design reference mission, with and without the coronagraph, on the basis of the science objectives, technical complexity, and programmatic rationale, including projected cost. The report reviews relevant scientific, technical, and programmatic changes that have occurred since the release of *New Worlds, New Horizons* and assesses the responsiveness of the WFIRST mission to the science and technology objectives of that report.

NAE member **A. Thomas Young**, Lockheed Martin Corporation, retired, was a member of the study committee. Paper, $48.00.

Health Standards for Long Duration and Exploration Spaceflight: Ethics Principles, Responsibilities, and Decision Framework. As the US space program evolves, propelled in part by increasing international and commercial collaborations, long-duration or exploration spaceflights become more realistic. But these types of missions will likely expose crews to levels of known risk that are beyond those allowed by current health standards, as well as risks that are poorly characterized, uncertain, and perhaps unforeseeable. As the National Aeronautics and Space Administration (NASA) and Congress discuss the next generation of NASA's missions and the US role in international space efforts, it is important to understand the ethical factors that drive decision making about health standards and mission design for NASA activities. This report was prepared in response to NASA's request that the Institute of Medicine outline ethics principles and practices to guide the agency's decision making about health standards for future long-duration or exploration missions.

NAE member **Bonnie J. Dunbar**, director, STEM Center, University of Houston, was a member of the study committee. Paper, $45.00.

At the Nexus of Cybersecurity and Public Policy: Some Basic Concepts and Issues. Cybersecurity is vital to protecting numerous day-to-day functions in defense, industry, transportation, health care, banking, and energy. Cybersecurity issues arise because of three factors: the presence of malevolent actors in cyberspace, societal reliance on IT for many important functions, and the presence of vulnerabilities in IT systems. This report offers a wealth of information on practical measures, technical and nontechnical challenges, and potential policy responses to protect government, businesses, and the public from those who would take advantage of system vulnerabilities. The report recognizes that threats will evolve as adversaries adopt new tools and techniques to compromise security, so cybersecurity also must evolve. The report is a call for action to make cybersecurity a public safety priority and to look beyond the short-term costs of improving systems.

NAE member **David D. Clark**, senior research scientist, Computer Science and Artificial Intelligence Lab, Massachusetts Institute of Technology, chaired the study committee. Paper, $44.00.

Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond. Convergence of the life sciences with the physical, chemical, mathematical, computational, engineering, and social sciences is key to tackling complex challenges and achieving new and innovative solutions. However, institutions lack guidance on how to establish effective programs, what challenges they are likely to encounter, and what strategies other organizations have used. This report describes organizations that have established mechanisms to support convergent research, program details, ways to measure success, and what has worked and not worked. The report summarizes lessons learned and presents strategies to tackle practical needs and implementation challenges in areas such as infrastructure, student education and training, faculty advancement, and interinstitutional partnerships.

NAE members on the study committee were **Joseph M. DeSimone** (chair), Chancellor's Eminent Professor of Chemistry, University of North Carolina, and William R. Kenan, Jr. Distinguished Professor of Chemical Engineering, North Carolina State University; **Cato T. Laurencin**, University Professor, Van Dusen Distinguished Professor of Orthopaedic Surgery, professor of chemical, materials, and biomolecular engineering, CEO, CT Institute for Clinical and Translational Science, director, Institute for Regenerative Engineering, and director, Sackler Center for Biomedical, Biological, Physical and Engineering Sciences, University of Connecticut; **Cherry A. Murray**, dean, School of Engineering and Applied Sciences, Harvard University; and **Nicholas A. Peppas**, Fletcher Stuckey Pratt Chair in Engineering, chair, Department of Biomedical Engineering, and professor, Departments of Chemical Engineering, Biomedical Engineering and College of Pharmacy, University of Texas at Austin. Paper, $44.00.

Review of Specialized Degree-Granting Graduate Programs of the Department of Defense in STEM and Management. The US military is arguably the most intensely technological, complex enterprise in existence. Major investments in weapons systems using advanced technologies provide an advantage over competing systems. Each weapon, platform, vehicle, and person in an operating force is a node in one or more advanced networks that enable the rapid formation of a coherent force from a large number of broadly distributed elements. DoD's ability to create and operate forces requires a competent understanding of the composition, acquisition, and employment of its technology-enabled forces. This report focuses on the graduate science, technology, engineering, mathematics, and management (STEM+M) education issues of the Air Force, Navy, and Marines. It assesses the cost, benefits, and organizational placement of DoD institutions that grant degrees in STEM+M and evaluates alternative ways—for example, civilian institutions and distance learning—to ensure adequate numbers and high-quality education outcomes for DoD personnel.

NAE members on the study committee were **Jacques S. Gansler** (chair), professor and Roger C. Lipitz Chair in Public Policy and Private Enterprise, and director, Center for Public Policy and Private Enterprise, University of Maryland, College Park; **Earl H. Dowell**, William Holland Hall Professor and Chair, Mechanical Engineering and Materials Science, Edmund T. Pratt Jr. School of Engineering, Duke University; **Wesley L. Harris**, Charles Stark Draper Professor of Aeronautics and Astronautics and associate provost, Massachusetts Institute of Technology; **Robert J. Hermann**, private consultant, Bloomfield, Connecticut; and **Stephen M. Pollock**, Herrick Professor of Manufacturing Emeritus, University of Michigan. Paper, $48.00.

Strategic Engagement in Global S&T: Opportunities for Defense Research. The US Department of Defense (DoD) has long relied on its historical technological superiority to maintain military advantage. But as the US share of science and technology (S&T) output shrinks and the US defense research enterprise struggles to keep pace with expanding security challenges and the increased speed and cost of global technology development, the DoD must reexamine its strategy for maintaining awareness of S&T developments around the world. The National Research Council was asked to assess Army, Air Force, and Navy strategies for leveraging global S&T and for implementing and coordinating these strategies across the DoD. This report explores models for global S&T engagement used by other domestic and foreign organizations, and assesses the potential impacts of S&T globalization on research funding and priorities and workforce needs as well as issues of building and maintaining trusted relationships and avoiding technology surprises. The report will be of interest to researchers and industry professionals with expertise in S&T globalization, international engagement, the defense research enterprise, program evaluation, and national security.

NAE members on the study committee were **Arden L. Bement Jr.** (cochair), Emeritus David A. Ross Distinguished Professor of Nuclear Engineering, director of the Global Policy Research and Global Affairs Officer, Purdue University; **Ruth A. David** (cochair), president and chief executive officer, ANSER; and **Katharine G. Frase**, vice president and CTO, IBM Global Public Sector, International Business Machines Corporation. Paper, $46.00.

Complex Operational Decision Making in Networked Systems of Humans and Machines: A Multidisciplinary Approach. Technology has vastly extended people's range of movement, speed, and access to massive amounts of data. Consequently, the scope of complex decisions has greatly expanded. But some technologies have also complicated the decision-making process, as advances in software, memory storage, and access to large amounts of multimodal data have dramatically increased. Human beings do not have the ability to analyze the vast quantities of computer-generated or -mediated data now available. How might humans and computers team up to use data for reliable (and when necessary, speedy) decisions? This report explores the essence of decision making; the vast amounts of data that have become available as the basis for complex decision making; and the nature of collaboration that is possible between humans and machines in making complex decisions. The report reviews research goals and milestones; impediments and systems-integration challenges preventing technological breakthroughs; and research in university, government, and industrial labs outside of the United States and its implications for US policy.

NAE members on the study committee were **Jacques S. Gansler** (chair), professor and Roger C. Lipitz Chair in Public Policy and Private Enterprise, and director, Center for Public Policy and Private Enterprise, University of Maryland, College Park; **Barbara J. Grosz**, Higgins Professor of Natural Sciences, Harvard University; **Anita K. Jones**, University Professor Emerita, School of Engineering and Applied Science, University of Virginia; **Tom M. Mitchell**, E. Fredkin University Professor and chair, Machine Learning Department, Carnegie Mellon University; **Donald A. Norman**, Breed Professor of Design and EECS Emeritus, Northwestern University, Honorary Professor, Design and Innovation, Tongji University, Shanghai, professor emeritus and director, UCSD Design Lab, University of California, San Diego, and cofounder, Nielsen Norman Group; and **Victor W. Zue**, professor of electrical engineering and computer science, Massachusetts Institute of Technology. Paper, $44.00.

The California Institute for Regenerative Medicine: Science, Governance, and the Pursuit of Cures. The California Institute for Regenerative Medicine (CIRM) was created in 2005 by the California Stem Cell Research and Cures Act (Proposition 71) to distribute $3 billion in state funds for stem cell research. During its initial period of operations, CIRM awarded more than $1.3 billion to 59 California institutions, consistent with its stated mission. As it transitions to a broader portfolio of grants to stimulate progress toward its translational goals, the institute should obtain cohesive, longitudinal, and integrated advice; restructure its grant application review process; and enhance industry representation in aspects of its operations. CIRM's unique governance structure, 'though useful in its initial stages, may diminish its effectiveness moving forward. This report recommends specific steps to enhance CIRM's organization and management, as well as its scientific policies and processes, as it transitions to the critical next stages of its research and development program.

NAE member **Cato T. Laurencin**, University Professor, Van Dusen Distinguished Professor of Orthopaedic Surgery, professor of chemical, materials, and biomolecular engineering, CEO, CT Institute for Clinical and Translational Science, director, Institute for Regenerative Engineering, and director, Sackler Center for Biomedical, Biological, Physical and Engineering Sciences, University of Connecticut, was a member of the study committee. Paper, $46.00.

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