Summer 2016

ISSUES AT THE TECHNOLOGY/ POLICY INTERFACE

The BRIDGE

LINKING ENGINEERING AND SOCIETY

NATIONAL ACADEMY OF ENGINEERING

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The
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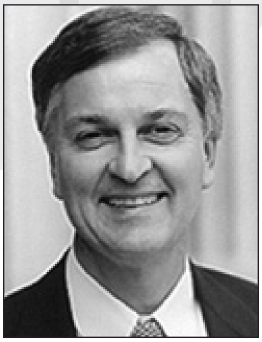
(continued on next page)

NAE News and Notes

Editor's Note



Ronald M. Latanision (NAE) is senior fellow, Exponent Failure Analysis Associates.

Issues at the Technology/Policy Interface

I am pleased to present in the following pages articles that address an array of matters involving both technology and public policy.

- Guru Madhavan and colleagues write on a subject of interest to all Americans, health policy decisions. They describe a systems-based tool that can enhance transparency in health policy decisions and be adapted in other policy areas. I am particularly pleased that former NAM president Harvey Fineberg and Rita Colwell (NAS), former NSF director, are among the authors of this article.

- Joseph Sinfield and Freddy Solis propose high-impact innovation for addressing large-scale sociotechnical challenges, using problem-solving methods that integrate contributions from a multiplicity of fields. They point out that innovation efforts have typically focused on the novelty and differentiation of an idea, rather than its impact.

- John Scully analyzes the water crisis in Flint, explains the fundamentals of lead corrosion in potable water, and calls for better technology stewardship, with examples of some tools to achieve this.

- Gretchen Jacobson reports on the new NACE global study, IMPACT—International Measures of Prevention, Application, and Economics of Corrosion Technologies, which focuses on segments of four major industries: energy, utilities, transportation, and infrastructure. She describes a corrosion management system framework as well as financial tools and other strategies for corrosion management.

  At this year's NACE conference, CORROSION 2016, the keynote speaker, television journalist Steve Kroft, appealed to NACE members to take action and help communicate to leaders and policymakers that the cost to fix or prevent infrastructure degradation is less than the cost of infrastructure failures.

  Together the Scully and Jacobson articles emphasize the critical need for attention to this country's infrastructure, which is aging and, as in Flint, abused. There are both political and technical issues associated with the state of the infrastructure in the United States. There seems to be nonpartisan agreement on the need for inspection, maintenance, and improvement, but there is a very clear partisan divide on how to pay for them.

- Bismark Agbelie, Samuel Labi, and **Kumares Sinha** (NAE) write about the need to recognize the funding shortfall for the maintenance of part of this nation's infrastructure, roads and bridges. They make the case for transitioning from the current fuel tax–based indirect funding mechanism to a direct user charging approach. The policy implications are clear and important.

- Kelly Grillo, Jane Bowser, and Tanya Moorehead describe tools and strategies that can be used in the classroom to help K–12 students identified with learning disabilities succeed in STEM courses, thereby encouraging them to pursue further education and careers in these fields.

- **Lionel Barthold** (NAE) and Dennis Woodford provide an update on DC power, largely abandoned more than a century ago and now making a comeback in generation, distribution, storage, and use. As the authors comment, "Edison would smile."

Jonathan Linton and **Daniel Berg** (NAE) follow with a well-crafted op-ed on the symbiosis of science and technology innovation. They offer the view that "There is a need to avoid well-meaning policy that creates unanticipated consequences that block the flow of knowledge between science, technology, invention, and innovation." This op-ed will resonate with many of our readers.

Our featured interviewee is Sandy Magnus, engineer and former astronaut, and now executive director of the American Institute of Aeronautics and Astronautics (AIAA). She is clearly a wonderful role model for young people in terms of engineering education.

Her comments reminded me of a YouTube video (www.youtube.com/watch?v=kqQuRPUy7zM&sns=em) about Professor Matt Mench of the University of Tennessee and three young women engineers who aspired to become involved with NASA…and were indeed hired by NASA. They have a great message for other young women and I recommend that you watch this. I thank Rusty Shunk, a high school classmate of my wife, Carolyn (Liberty High School, Bethlehem, PA), and former executive vice president at Dickinson, for bringing Matt Mench and the University of Tennessee students to my attention.

The NAE is very interested in encouraging young women to become engineers; its program *EngineerGirl* (www.engineergirl.org/) is an excellent example of its efforts in this area. And the annual Engineering for You (E4U) video contest (https://www.nae.edu/e4u3/) aims to develop public understanding of and engagement in engineering.

The fall issue will focus on OpenCourseWare.

As always, I welcome your comments and feedback at rlatanision@exponent.com.

We describe a systems-based platform that can facilitate discussion among stakeholders and promote convergence and transparency in policy decisions.

In Plain View

A Transparent Systems Approach for Enhancing Health Policy Decisions

Guru Madhavan, Charles E. Phelps, Rita R. Colwell, Rino Rappuoli, and Harvey V. Fineberg

Guru Madhavan

Charles E. Phelps

Rita R. Colwell

Rino Rappuoli

Harvey V. Fineberg

Modern times bring modern complexities that call for strategic priority setting. Markets effect some prioritization through the willingness of people to buy and sell products at competitive prices. Other activities—such as public investments in defense, regulation, research, and health services—take

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Guru Madhavan is a program director in health and medicine, National Academies of Sciences, Engineering, and Medicine. Charles E. Phelps (NAM) is university professor and provost emeritus, University of Rochester. Rita R. Colwell (NAS) is a distinguished university professor, University of Maryland, College Park and Johns Hopkins Bloomberg School of Public Health, and former director, National Science Foundation. Rino Rappuoli (NAS) is chief scientist, GlaxoSmithKline Vaccines. Harvey V. Fineberg (NAM) is president, Gordon and Betty Moore Foundation, and past president, Institute of Medicine.

The views expressed in this article are those of the authors and not necessarily those of the National Academies of Sciences, Engineering, and Medicine.

place outside of the market and benefit from careful planning, especially as resource constraints loom large in every sector.

In health and health care, global forces such as emerging and reemerging diseases, aging and associated disease burdens highlight the critical need for better understanding of the links between human behavior, culture, and environment to improve outcomes. We describe a systems-based tool that accounts for these factors and their influences while at the same time promoting convergence and transparency in the decision-making process.

Actual policy decisions take various factors into account in ways that are often hidden from public view and discussion.

Cost-Effectiveness Analysis

In the best of circumstances, planning and prioritization are informed by data and evidence, and many approaches have evolved accordingly. Using accounting and budgeting techniques, early planning efforts focused on program costs, which are easier to measure than outcomes and benefits. Then cost-benefit analysis emerged, providing a mechanism to combine both costs and benefits in widely diverse areas of policymaking.

Many health policy analysts use a similar approach, called *cost-effectiveness analysis*. While cost-benefit assessments place an explicit value on a life saved or a life-year gained, cost-effectiveness analyses measure health benefits in natural units such as life-years saved or premature deaths averted irrespective of age. The priority-setting process then uses the ratio of incremental costs to incremental health gains—the incremental cost-effectiveness ratio—as a ranking metric.

Health policy analysts and decision makers are often reluctant to set a specific monetary value on lives saved, quality-adjusted life years (QALYs) created, or disability-adjusted life years (DALYs) reduced. For this and other reasons, the World Health Organization recommends the use of a generalized cost-effectiveness analysis to evaluate health programs, eschewing the potentially more complete cost-benefit framework (Tan-Torres Edejer et al. 2003).

Invariably, however, cost-benefit and cost-effectiveness analyses cannot meaningfully incorporate positive or negative externalities that affect individuals who do not receive the intervention in question. They also omit many important factors that determine real policy decisions, such as socioeconomic inequality, public perception of a disease, or faith-based practices. Cost-effectiveness analyses typically carry a caveat to that effect.

Actual policy decisions take these other factors into account, but in ways that are often hidden from public view and discussion. We urge that these factors be brought into plain view as part of the formal decision analysis.

Subjective Attributes

In common practice, decisions about priorities (and actions that follow) rely on a blend of hard analysis and subjective attributes. How these qualitative attributes are weighted in the decision, and how they are combined with data-driven cost-effectiveness and cost-benefit exercises, is not articulated and may not even be explicitly recognized. How much emphasis does each attribute receive in the final decision? In general, there is no way to know. Preferences differ among various stakeholders, and it may not be worthwhile to argue about them: *De gustibus non est disputandum* (Stigler and Becker 1977).

Consider the domain of vaccine development. Vaccines prevent disease from occurring, and some offer the promise of wholly eradicating the disease. Prevention means that something does not happen, and is therefore hard to measure. (The nonoccurrence of disease or disability is also hard to measure in comparison to dramatic therapeutic interventions such as organ transplants, synthetic joints, or vision-restoring surgery.)

But because vaccines often have their greatest impact in early years of life, their ability to maintain a child's health can lead to better growth, education, and development, greater lifetime earnings, and thus the improved success of subsequent generations (Rappuoli et al. 2014; Whitney et al. 2014). They can even, ultimately, lead to changes in family fertility decisions, and thus population growth (Montgomery and Cohen 1998) and eventual infrastructure requirements. Because few health interventions offer such dramatic and far-reaching prospects, the application of standard analytical techniques such as cost-effectiveness and cost-benefit to vaccines and other global health interventions is simply inadequate.

Similarly difficult to capture in a conventional cost-effectiveness analysis are issues that arise when the relevant disease—Ebola is a prime example—generates significant anxiety and fear, elements that are typically omitted from cost-benefit or cost-effectiveness models. This challenge is amplified by differing and even conflicting views and values among different stakeholders in the vaccine enterprise.

In the face of such difficulties, alternative techniques that rely on multicriteria systems analysis have greater potential to successfully incorporate the other, nonobjective factors that often drive real-world decisions.

A Systems-Based Tool

Systems-based approaches seek to include all relevant aspects of a decision in a cohesive model that treats all factors comparably by explicitly defining them and assigning them a weighted importance.

SMART Vaccines

In a recent project funded by the US Department of Health and Human Services, the National Academies of Sciences, Engineering, and Medicine developed a systems-based software for vaccine prioritization called the *Strategic Multi-Attribute Ranking Tool for Vaccines (SMART Vaccines)* (Madhavan et al. 2012, 2013, 2015).[1]

SMART Vaccines integrates diverse elements that influence important decisions in a single unifying framework. The model creates a value score for each possible vaccine candidate, based on how well each choice performs against a standardized scale pertinent to each attribute, and then applies weights *determined by the user/stakeholder* that specify the importance of each attribute to produce a final SMART score. The key feature is the ability to specify each attribute on a common 0 to 100 scale, where nominally zero represents the worst-case and 100 the best-case performance of the candidates.

For example, one attribute measures premature deaths prevented by a vaccine, calculated using data on disease burden, breadth of the vaccination program's coverage, and the vaccine's efficacy. A score of zero would denote no deaths prevented, and a score of 100 might represent, for example, the highest envisioned achievement: elimination of half of a population's deaths from the most serious known vaccine-preventable disease. Other high-end achievements associated with vaccine use could include enhanced quality of life, workforce productivity, and educational attainment. The value of some attributes will be subjectively assessed depending on the particular context—whether the vaccine fits into an existing immunization schedule, avoids the use of cold-chain storage, or benefits target populations (e.g., low-income, military, or native groups).

Once each vaccine's attributes are measured on the 0 to 100 scales, its overall performance is measured by adding up these attribute-scores, weighted by the importance the user/stakeholder places on each attribute (with the weights summing to 100 percent). The scores are unique to each user since the weights are user-specified.

Techniques that use multicriteria systems analysis can better account for nonobjective factors that often drive real-world decisions.

Applications and Advantages

One direct application of this systems approach is to create a set of possible vaccine strategies (e.g., one, two, or three doses, or increased length of protective immunity) and compare the SMART scores in real time as certain attributes assigned to the vaccine candidates are varied.

As an example, consider pneumococcal vaccines: Would it be more desirable to add more serotypes to the vaccine to increase efficacy or to reduce the number of doses required to achieve a given level of protection, and at what cost? How do these recommendations change if some pneumococcal strains become increasingly resistant to antibiotics?

Perhaps the most important advantage of the systems-based approach is that it brings the decision-making process into full view: How each candidate vaccine performs on each dimension is measured comprehensively. If different people have different estimates of these perfor-

[1] SMART Vaccines version 1.1 is a Windows-based desktop application and can be downloaded free of charge from www.nap.edu/smartvaccines.

mances, the differences are obvious and can be resolved through discussion and/or better data. If different people have different preferences (i.e., they weight attributes differently), those differences are clear, since the weights are exactly specified and can be clearly seen and compared across stakeholders. Groups or organizations can create their own official list(s) by agreeing on relevant attributes and associated weights.

Facilitated Discussion and Convergent Decisions: A Hypothetical Illustration

To illustrate how multicriteria systems analysis can facilitate discussion and lead to convergent decisions among possibly competing stakeholders, we created a scenario using SMART Vaccines involving negotiations between a hypothetical health minister and finance minister. In our demonstration, the ministers seek convergence on the prioritization of three hypothetical vaccine candidates for the South African population—rotavirus for infants, or pneumonia or tuberculosis for all ages.

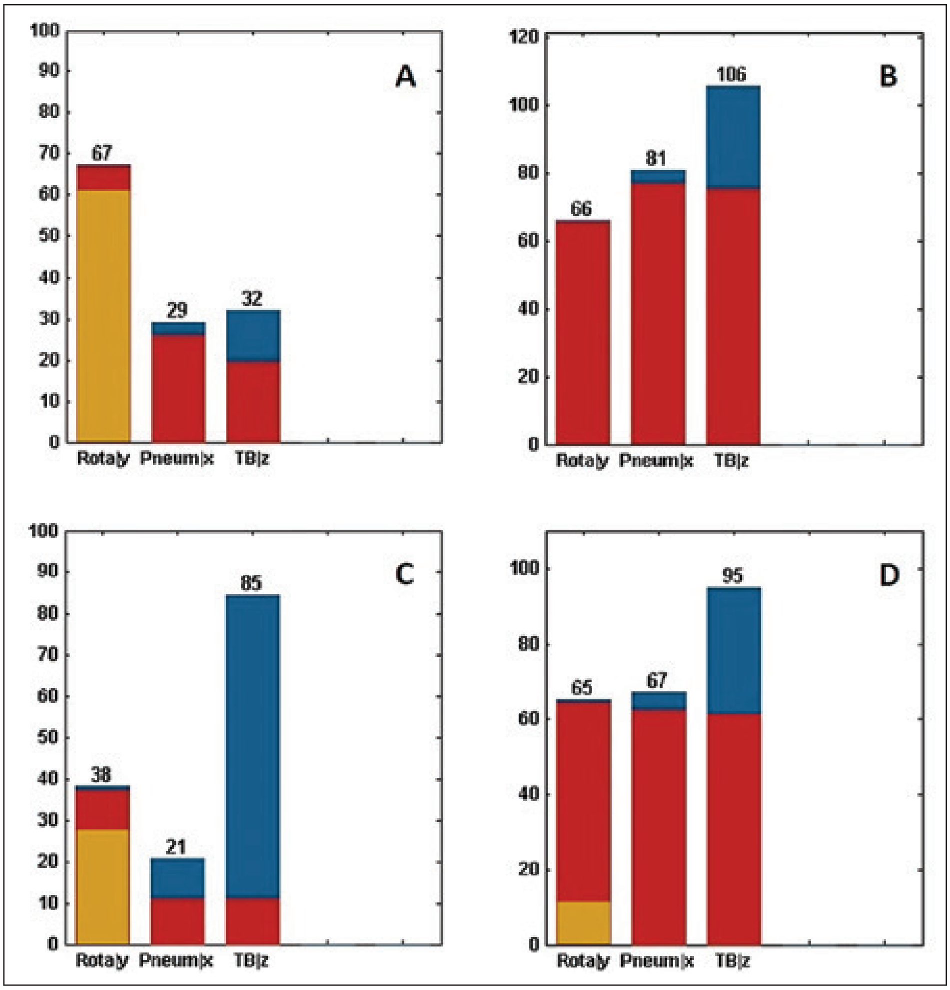

FIGURE 1 A discussion facilitation scenario using SMART Vaccines involving a vaccine investment negotiation between a hypothetical health minister and finance minister of a developing country. Both seek convergence on the choice of a vaccine candidate from three options: rotavirus (rota-y) for infants, pneumonia (pneum-x) or tuberculosis (TB-z) for all ages. The colors indicate the contribution of health (blue), economic (red), and demographic (yellow) attributes to the SMART scores. In the health minister's initial analysis (panel A), with a significant emphasis on a vaccine that benefits infant and children, the rotavirus candidate outranks pneumonia and tuberculosis. The finance minister's emphasis (panel B) on economic benefits yields a top score for the tuberculosis vaccine. The discordance between the ministers' choices is clearly shown by the transparency in SMART scores. After negotiation, the ministers agree to use a different set of attributes and the resulting analysis creates convergence in their decision: the tuberculosis vaccine scores the highest for both the health (panel C) and finance (panel D) ministers.

They approach their discussion having used SMART Vaccines with their own predetermined set of attributes and associated weights.

- The health minister's selection includes three attributes: the potential of the vaccine to benefit infants and children (as a specific demographic consideration, ranked first with 61 percent weight, but applied only to the rotavirus vaccine), premature deaths averted (to represent health benefits, ranked second with 28 percent weight), and net direct costs or savings associated with vaccine use (as an economic factor, ranked third with 11 percent weight).
- The finance minister's selection involves two attributes: cost-effectiveness calculated as cost per disability-adjusted life years ($/DALY; ranked first with 75 percent weight) and DALYs averted (ranked second with 25 percent weight)—with the understanding that the DALYs averted measure will also capture

much of the potential workforce productivity gains in which the minister has interest.

As figure 1 shows, the ministers arrive at discordant priorities. The health minister shows rotavirus vaccine as the top performer (a score of 67) compared to the finance minister's leading candidate, the vaccine for tuberculosis (a score of 106, exceeding the envisioned best score of 100). The absolute value of each minister's SMART scores has no meaning in comparison to others' scores; rather, each individual's weights create an independent and unique yardstick to gauge vaccine ranking *for that individual.*

In discussing their chosen attributes and weights, the two ministers come to agree that using the DALYs averted measure could capture much of the health minister's concern expressed in the earlier combination of life years saved and special benefits to infants and children. They also come to agree that the finance minister's cost-effectiveness metric ($/DALY) captures in large measure the fiscal concerns expressed by the health minister's use of net direct costs or savings. But the health minister insists that the special benefit of rotavirus vaccine for infants and children is still important, independent of the technical value of DALYs.

Using SMART Vaccines as a facilitator, the ministers agree on a new set of three attributes for a reanalysis: DALYs averted, $/DALY, and benefits to infants and children. The health minister ranks DALYs averted first, benefits to infants and children second, and $/DALY third (the updated scores are in panel C of figure 1). The finance minister ranks in the order of $/DALY, DALYs averted, and benefits to infants and children (panel D). Despite the difference in ranking of the attributes they have chosen, they now converge on a shared decision for a vaccine candidate: tuberculosis ranks first.

Looking Ahead

In addition to the obvious uses of this software for vaccine prioritization, we envision an extended set of applications based on the core platform that underpins SMART Vaccines. Adaptations of the software could be applied to

- evaluating benefits of diagnostics, therapeutics, informatics, or interventions (say, SMART Health);
- prioritizing among existing or new technology options to reduce the burden of leading chronic diseases (SMART Prevention);
- assisting patients' choices among alternative treatment options (SMART Choices);
- analyzing response and countermeasure efforts against infectious pathogens (SMART Preparedness);
- considering insurance benefit design (SMART Benefits);
- exploring pricing options for various prescription drug programs (SMART Pricing);
- ranking endpoints/outcomes in clinical trial design (SMART Trials), and
- supporting allocation decisions about investments for innovation in science, engineering, and health (SMART Innovation).

All of these, of course, would require further software development and relevant data, but it is clear that the potential applications of multicriteria systems analysis and decision support are extensive.

It is time to make otherwise hidden and subjective elements of major policy decisions visible and transparent.

We believe it is time to make otherwise hidden and subjective elements of major policy decisions visible and transparent. Globally, the pressure for sound policy decisions is rising in areas not subject to pure market resolution—defense, regulation, research, population health, and others. And recent developments in online social media (e.g., Twitter, YouTube, Facebook, and Instagram) reveal a public now accustomed to transparency. Governmental policy and decision making must accommodate to this reality.

From our experience in developing SMART Vaccines, we believe that policy tools can be designed to incorporate a wide variety of stakeholder preferences. SMART Vaccines is a tool that can serve as a prototype to stimulate product development efforts that facilitate discussion and deliberation among stakeholders and thus promote transparency in policy decisions.

Acknowledgments

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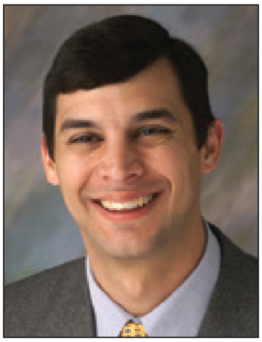
High-impact innovation to address major challenges requires ideas that achieve broad reach, comprehensive significance, paradigm change, and longevity.

Thinking Big to Address Major Challenges

Design and Problem-Solving Patterns for High-Impact Innovation



Joseph V. Sinfield

Freddy Solis

Joseph V. Sinfield and Freddy Solis

The world's most pressing challenges are testing the limits of existing approaches to problem exploration, innovation, and design. Be it equitable provision of clean water (OECD 2012), creation of single-dose vaccines (Varmus et al. 2003), clean-energy agriculture (Ferguson 2014), or restored and improved urban infrastructure (NAE 2008), complex systems-level problems that broadly affect society are driven largely by the extraordinary growth in the human population and its demand for essential resources such as water, food, and energy, as well as the compounding implications that manifest as longer human lifespans increase encounters with formidable medical conditions.

Characterizing Major Challenges

While many examples of important local-scale success stories in these and similar problem areas exist and should be lauded, achieving success of the reach and significance required to comprehensively address major challenges has proven vexing (Cohen 2006; Hait 2010; Wulf 2000), exposing multiple failure modes such as lack of adoption, funding shortages, unanticipated system behaviors, and technical barriers. Major challenges are thus perceived

Joseph V. Sinfield is associate professor of civil engineering and Freddy Solis is postdoctoral research associate, both at Purdue University.

to be daunting, complex (both figuratively and technically), and, by many, intractable.

Partly, the difficulty in addressing such challenges stems from the differing nature of needed solutions. Some require fundamental scientific breakthroughs, others await development of enabling innovations (Solis and Sinfield 2015), and still others call for efficient democratization of established capabilities in unique circumstances. These solutions span technical, economic, social, and cultural domains, and thus impede approaches derived from only one perspective. Definitive improvements that can be translated into long-lasting, significant impact thus remain infrequent in most domains.

Solutions to major challenges span technical, economic, social, and cultural domains, and thus impede approaches derived from only one perspective.

However, major challenges also share many characteristics. Commonalities can be seen in the systems, complexity, design, and innovation domains, all of which are ambiguously bounded, involve multiple stakeholders and interdependencies, and display nonlinear emergent behavior, network effects, and hysteresis (e.g., Barabasi and Bonabeau 2003; Maroulis et al. 2010; Mostafavi et al. 2011; Norman and Stappers 2015). Effective solutions likely require prioritization and accommodation of stakeholder needs, development and diffusion of new technology, and conversion of habits to realize change—perspectives frequently considered in isolation in the design and innovation domains.

Together, these characteristics suggest that large-scale sociotechnical problems could be more systematically addressed through problem-solving methods that integrate contributions from all these fields. What is needed are frameworks and vocabulary that facilitate concept sharing across communities and link actionable innovation behaviors to society's greatest needs.

Changing the Focus of Innovation from Novelty to Impact

This article puts forward a qualitatively different approach to design (problem solving) for major challenges, emphasizing a proactive focus on high-impact innovation. This is a different emphasis than is classically pursued in innovation efforts, which focus on the novelty and differentiation of an idea rather than its impact. Impact, if examined at all, is typically considered retrospectively.

In fact, until recently there was no definition of innovation impact. Recent research (Solis and Sinfield 2015) has taken a first step in this direction by breaking impact into four fundamental dimensions:

- *reach:* the number of individuals, groups, or societal segments affected by an innovation;
- *significance:* the magnitude of benefit across measures of economics, health, environment, and culture;
- *paradigm change:* the degree to which an innovation alters implicit or explicit worldviews in a particular domain; and
- *longevity:* the timespan over which an innovation has influence.

Thus, in addition to searching for the novel and different, the act of innovating should focus on driving new solutions toward achieving impact as characterized by these four criteria.

Research has shown that the way one approaches a problem changes the nature of the resulting solution (Chi and Hausmann 2003; Dorst 2015; Grant and Berry 2011; McCaffrey 2012). Some have framed the notion that design activities vary according to the nature of desired goals, using the phrase *design for x*, where *x* represents a goal. As such, recently uncovered patterns of high-impact innovation suggest that big ideas—such as anesthesia, vaccines, transistors, or microfinance—with the potential for meaningful and long-lasting impact require thinking big, considering "outcomes" early and often while innovating, and proactively designing for *Big X*.

Designing for "Big X"

We present a conceptualization of a means to design for Big X developed from a scholarship of integration activity (Boyer 1990) that sought larger intellectual patterns by connecting insights from three lines of research (Solis 2015):

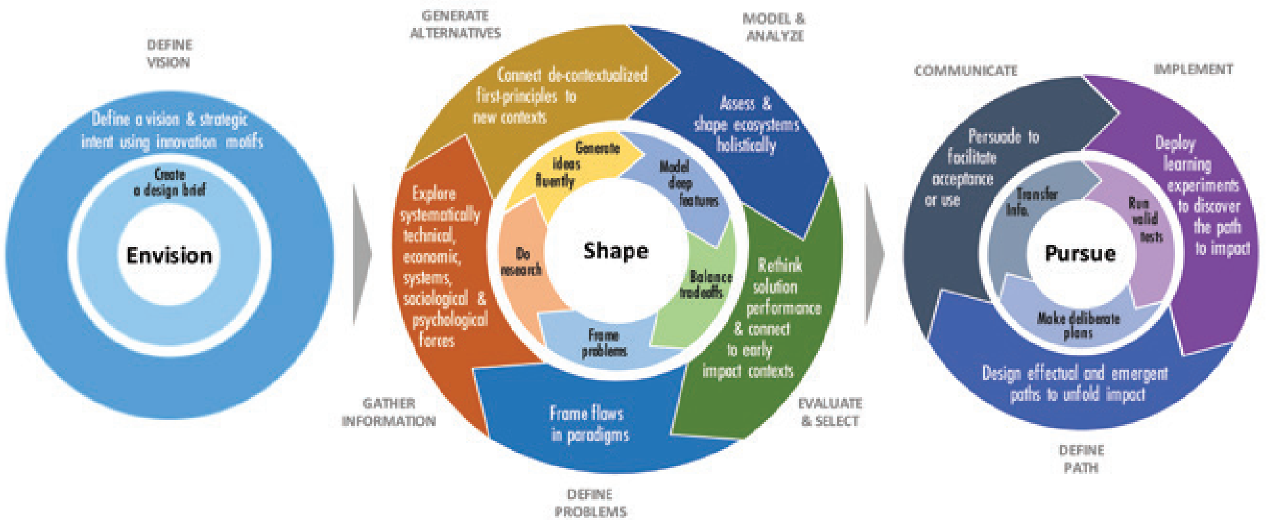


FIGURE 1 Design Shifts for "Big X." Contrasts between generic design and "design for Big X" patterns are shown for an end-to-end model of design activities to envision, shape, and pursue innovation. The inner ring represents generic design capabilities, applicable to a broad array of problem-solving circumstances. The outer ring represents qualitative shifts in design capability for the specific case in which a problem solver needs to design for Big X, representing a high-impact innovation needed to address a major challenge.

1. meta-synthesis encompassing systems, complexity, innovation, entrepreneurship, and design literature;
2. search for evidence of design behaviors across historical cases of high-impact technical and conceptual innovations, such as anesthesia, vaccines, transistors, the X-ray, and microfinance; and
3. verbal protocol analysis of performance tasks completed by 20 innovators in industry and academia, who were asked to describe their approach to the representative major challenge of significantly increasing adoption of electric vehicles (EVs) in the United States.

Each method provided a perspective on innovation in complex contexts—research, history, and practice—which were then integrated. The result is a conceptual model that highlights shifts in problem-solving approaches for major challenges and is tied to an end-to-end conception of a design process, as illustrated in figure 1.

These shifts, described below, are significant in that they depart from hierarchies of generic design capability (Crismond and Adams 2012) and encompass activities to envision, shape, and pursue a new idea in which impact acts as a problem-solving guide.

Envisioning Big Ideas

From Design Briefs to Long-Term Visions Guided by Motifs

The first shift to design for Big X sets an aspirational goal for big ideas by *defining a vision and strategic intent using innovation motifs*. Because of the potential to get lost in the myriad issues that underlie complex challenges, it is critical to enter the design process with a long-term vision that encompasses the full scope of sought-after solutions. This is more than the typical focus on objectives, constraints, or performance characteristics stated in design briefs.

The vision should encompass a perspective on how the design outcome will affect its host ecosystem, the intent of the impact, and possible starting points for realization of the idea. To guide this aspiration, one can employ *motifs*, flexible design guides common in other design-based disciplines (e.g., in architecture, art deco or Prairie style). Motifs provide thematic considerations that help prioritize design choices. For example, when developing a technology for an emerging market, a disruptive motif would suggest that performance tradeoffs are acceptable in order to achieve affordability, accessibility, or ease of use (Anthony et al. 2008).

In efforts to create visions for high impact, innovation motifs can be used to relate a problem type to a solution form and its potential impact. The established motifs of enabling (Solis and Sinfield 2015) and competency-enhancing innovation (Abernathy and Clark 1985), as well as general purpose technology (Bresnahan and Trajtenberg 1995), can all describe not only the novel nature of a solution but also aspects of its impact on the problem at hand.

When combined, visions and motifs create aspirational yet actionable guides for success. The development of microfinance (Yunus 1999), for example, emerged from the aspiration of providing financial services for the poor. Grameen Bank, one of the first in this space, is an excellent example of an enabling innovation motif, as it was designed to drive a paradigm change in banking practices. Other innovations, such as insurance, transistors, and GPS, followed similarly aspirational visions.

> *"Thinking big" requires systematic exploration of technical, economic, systems, sociological, and psychological forces that may act on a promising concept.*

Shaping Big Ideas

From Framing Isolated Problems to Framing Flaws in Paradigms

As mentioned, research suggests that the way a problem is framed inherently constrains the set of solutions one can develop. When designing for Big X, the stage is set for big ideas by *framing flaws in paradigms*. This approach identifies opportunities to change worldviews by uncovering important assumptions in problem and solution spaces.

Surfacing hidden assumptions—and attempting to proactively counter them—can help unearth new challenges and possibilities. Doing so entails going beyond framing isolated problems to question the validity of old assumptions and frameworks (Chi and Hausmann 2003; Sitkin et al. 2011), and unearthing not only what is known but also what is not known because it is inherent (hidden) in cultural and historical traditions or is at the outer limits of the body of knowledge.

Anesthesia, for instance, addressed the hidden assumption that pain in acute circumstances, such as surgery, was a normal part of life (Gawande 2012, 2013). Advancing the concept of the laser required reexamination of the assumptions of thermal equilibrium underlying the 2nd law of thermodynamics (Townes 1999). Microfinance challenged flawed assumptions in banking systems.

The paradigm framing approach was also evident in the performance tasks observed in our research, which revealed significant differences in solution scope and richness between participants who simply listed problems with EVs and those that more deeply examined transportation paradigms to search for hidden assumptions. The former talked primarily of technical solutions, whereas those who challenged the transportation paradigm tended to integrate economic incentives, governmental policy, sociocultural issues, and broader infrastructure considerations in their proposed solutions.

From Focused Research to Systematic Multiscale, Multifaceted Exploration

Big ideas often face multiple types of resistance, making deep investigations of focused issues valuable but likely insufficient. When one thinks of a big idea and its broad adoption, many categories of issues emerge (e.g., technical, legal, social). "Thinking big" thus requires *systematic exploration of technical, economic, systems, sociological, and psychological forces* that may act on a promising concept.

The adoption of X-rays in the medical field, in the first half of the 20th century, for instance, encountered sociological barriers rooted in power struggles between X-ray technicians, physicians, and the nascent field of radiology (Kevles 1997). Technical issues also had to be overcome, like the resolution of X-ray machines, which was addressed through the development of Coolidge tubes and ray collimation techniques. Although these issues were ultimately solved, failure to anticipate and tackle them slowed adoption.

Similarly, in our study, a range of issues were raised in the performance tasks, from battery range and charging speed to economics, commuting patterns, and emotional attachment to cars. Stronger innovators attempted to systematically explore this set of issues to develop a comprehensive view.

Focusing on a single issue or scale may obscure others. Opportunities to accelerate adoption of big ideas become more apparent when a broader view of a challenge is considered early in the design process.

From Analogies to Thinking from First Principles

Typically, idea generation relies on techniques such as lateral thinking, heuristics, and analogies (Ahmed and Christensen 2009; de Bono 1975; Yilmaz and Seifert 2011). But when ideas are new to the world and represent a true paradigm change, the possibilities for thinking by analogy are somewhat limited. To think big, "idea spaces" themselves must broaden, and one way to do so is by *connecting decontextualized first principles to new contexts*.

Research on physics education suggests that thinking from first principles provides another alternative: getting to the fundamental core of ideas to derive new possibilities (Chi et al. 1981; Larkin et al. 1980; Stinner 1989). Connections of first principles to other ideas and/or application spaces create nonobvious opportunities to advance solution capabilities and impact. Jargon-free language that describes first principles without discipline-specific implications is critical to facilitating such links.

Consider the laser. When described as a coherent energy source that can precisely ablate material, many domains emerge in which this first principle has value—surgery, dentistry, manufacturing, cleaning. Thus, big thinkers might prioritize ideas with more first principle potential over others.

From Modelling to Assessing and Shaping Ecosystems

Thinking big also involves *assessing and shaping ecosystems holistically* because successful big ideas often proactively incorporate in their design elements that tackle ecosystem barriers. Embedding such elements implies thinking beyond a solution to consider how it interacts with a system.

This philosophy emphasizes "framing and solving" the ecosystems in which a solution will play a role, especially those that may host a solution in its path toward success. Insights from the systems literature shed light on this concept (Adner and Kapoor 2010; DeLaurentis and Ayyalasomayajula 2009; DeLaurentis and Callaway 2004; Maroulis et al. 2010).

Making early microfinance initiatives work required going beyond the creation of loan mechanisms for the poor. It entailed developing support groups in villages that encouraged repayment and proper use of funds, as well as policies and training adequate for areas with high illiteracy rates; hosting meetings in open spaces to inspire trust and reduce corruption; and identifying ways to overcome gender bias (Yunus 1999).

Connections of first principles to other ideas and/or applications create nonobvious opportunities to advance solutions and impact.

From Moonshots to Lily Pad Performance Development

Rethinking solution performance and connecting to early impact contexts may make it possible to accelerate and "de-risk" high-impact efforts. This philosophy focuses on agglomerating and disaggregating capabilities to create new notions of performance that can achieve early impact in contexts often different from the context of the overall goal. This goes beyond mapping and balancing solution tradeoffs (Kim and Mauborgne 2005) to include assessment of capability variations, performance trajectories, and context as key variables.

At early times in the development of an innovative solution, the solution is unlikely to be ready for its ultimately envisioned application. However, this does not limit its potential to be applied and to gain faster adoption in contexts outside of traditional boundaries. Searching for performance-context opportunities that are right for the currently achievable level of performance can thus uncover new, counterintuitive paths to the overall vision for a big idea, avoiding reliance on "achieving the moonshot" to make progress. Collectively, a succession of these opportunities resembles a roadmap of stepping stones, or "lily pads," that simultaneously advance performance, de-risk efforts, and refuel an innovation.

For X-rays, lily pads included short stints in department store entertainment, shoe fitting, customs inspection, and forensics before moving into dental and medical practices (Kevles 1997). X-rays thus made multiple lily pad "jumps" prior to broad adoption. For big ideas, these jumps across domains have historically occurred serendipitously, often over great lengths of time; but they can be pursued by design.

Pursuing Big Ideas

From Information Transfer to Persuasion

In the communication of big ideas, simply transferring information is not enough. Driving changes to worldviews and altering ecosystems requires artful *persuasion to facilitate acceptance or use*. This may involve stories, habit conversion techniques, and means to convey counterintuitive insights (Denning 2004; Graybiel 2008; Graybiel and Smith 2014; Kegan and Lahey 2009). These techniques tap emotion, empathy, and human nature, and are key to addressing the natural resistance to new ideas; stories, for example, help paint visions and trigger emotions that enhance idea adoption (Heath et al. 2001; Heath and Heath 2007).

Artful persuasion is needed to address the natural resistance to new ideas and facilitate their acceptance or use.

In a preanesthetic world, for instance, surgeons were used to operating quickly to minimize patient suffering, and even after anesthesia's invention some surgeons continued to proceed in their rushed ways—spectators even timed them with pocket watches (Gawande 2012). It took significant persuasion—through public surgical exhibitions, press coverage, and rigorous academic publications—to encourage the community of surgeons to adjust their habits—and to convince society that, despite resistance from some clergy and physicians who considered pain a natural part of life, anesthesia was a much needed paradigm change (Gawande 2013).

From Predicted and Deliberate to Emergent and Effectual Pursuit

Big ideas can take many implementation paths, so the design of implementation strategies is critical. In *designing effectual and emergent paths to unfold the impact of a big idea*,[1] implementation strategies are defined by mapping and converting key assumptions necessary to achieve impact into actionable learning experiments. These experiments should aim to test and validate big idea assumptions—such as performance limitations, uncertainty in application spaces, and ecosystem-level barriers (Blank 2005; McGrath and MacMillan 1995; Mintzberg and Waters 1985). They also entail imagining new goals and means given existing means, resources, and relationships (Sarasvathy 2009). These implementation strategies are then pursued by *deploying learning experiments to discover the path to impact*, prioritizing opportunities to earn (for economic sustainability), learn (for solution improvement), and redirect efforts in light of learning.

In the early history of transistors, for example, interests shifted back and forth between germanium and silicon as candidate materials for semiconductors (Isaacson 2014). In our EV tasks, participants proposed experiments to learn what would drive adoption, focusing on sensitivity to gas prices, density of charging stations, urban community characteristics, and tax subsidies. The uncertainty around these issues makes predictive approaches less useful than emergent and effectual ones.

Implications

The unique shifts in behavior needed to design for Big X appear consistently in historical examples of high-impact innovation, are reinforced by connecting insights gleaned in multiple related fields, and are evident in the problem-solving strategies of contemporary innovators. Such an innovation framework is not positioned as better or more advanced than other approaches; it simply provides new entry points into the innovation process for problem solvers.

Awareness of these behaviors can help leaders in various types of organizations drive new kinds of solutions to a range of complex problems in the form of big ideas that can alter the way individuals, groups, and society live and act:

- For governments and nonprofits, they could lead to answers to society's major challenges.

[1] "Emergent" here is the opposite of "deliberate." Essentially, it refers to an unpredictable and unanticipated path that unfolds as progress is made. This term is broadly used in strategic management literature in relation to a seminal article by Mintzberg and Waters (1985).

- For companies, they could lead to innovations that drive growth with longevity.
- In academia, they could highlight new avenues for high-impact research and new ways to teach students to innovate.

In addition, each of the philosophies described here can help leaders understand whether stakeholders are asking the right questions about promising concepts to drive breakthroughs toward impact. They can also help assess whether the right people (with the right mindset) are involved in big idea projects—whether innovation teams are balanced in terms of insights and perspectives as well as expertise, because no individual is likely to excel in all areas.

Perhaps more importantly, these behaviors can help inform pedagogy for innovators of the future, encouraging them to proactively and systematically outline conceptual problem-solving shifts when needed. Awareness and practice of these competencies will be valuable to all organizations and individuals pursuing significant impact in the world.

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The situation in Flint underscores the need for change in the handling of complex technological problems with high risk.

The Corrosion Crisis in Flint, Michigan

A Call for Improvements in Technology Stewardship

John R. Scully

John R. Scully is interim chair, Charles Henderson Endowed Chaired Professor of Materials Science and Engineering; Technical Editor in Chief, CORROSION; and co-director, Center for Electrochemical Science and Engineering, University of Virginia.

The water contamination crisis in Flint, Michigan, vividly demonstrates that the current approach to technology stewardship in the face of problems that may lead to calamity is not working. Lessons often are tragically *not* learned or used during decision making.

A more proactive approach to technology stewardship, risk assessment, and public policy practice is recommended, drawing on lessons from previous experiences and supporting timely, data-driven decisions and actions by well-informed authorities. Without such cultural and behavioral change, there is the risk of repeating technological mistakes and encountering disasters again and again with enormous costs in public health and public trust and at great taxpayer expense (Koch et al. 2016).

This article suggests tools for anticipating and managing potential problems before they produce a calamity.

The Flint Water Crisis: A "Perfect Storm"

The situation in Flint can be traced to the original decision to use lead piping and then a series of unfortunate choices and missed opportunities, starting with the switch to Flint River water followed by a failure to follow federally recommended corrosion control measures.

It has been noted that the location of the lead pipe in Flint's water supply and distribution system cannot be readily ascertained. Documentation of lead pipe use in the city is recorded on 45,000 index cards and stored in a public utility building, making it difficult to determine which end consumers are connected to lead pipe (Fonger 2015).

The city's drinking (potable) water supply was switched in 2014 from Lake Huron to the Flint River to save money while the city was under state emergency management (Adams 2014). The significantly more corrosive Flint River water chemistry caused faster lead release into the city's potable water as well as rampant iron corrosion (Edwards 2015a,b; Edwards et al. 2015). The iron corrosion led to brown water and may have helped to trigger the growth of *Legionella* bacteria via an established pathway (State et al. 1985).

In June 2015 an EPA memorandum to the Michigan Department of Environmental Quality (MDEQ) noted that maximum contamination levels for coliform were exceeded 5 times (Del Toral 2015). It pointed out violation of a federal guideline (the LCR[1]) based on high lead levels measured in selected Flint homes, and reminded the MDEQ of the requirement to provide corrosion control for all water systems serving more than 50,000 customers in order to limit lead release (Del Toral 2015).

The problems in Flint constituted a perfect storm of corrosive water, lack of corrosion control, and ineffective water testing.

It appears, however, that the MDEQ was uninformed about LCR sampling guidance (40 USC. Sec 141.86[2]) and/or used questionable sampling methods to produce results that would not exceed the maximum lead levels requiring action. Practices alleged include the exclusion of samples with high lead, claims that the homes themselves (even those with plastic pipes) were the source of lead, and the flushing of faucets before lead sampling (Del Toral 2015; Edwards 2015c; Edwards et al. 2015). Independent lead sampling was criticized and its results even ridiculed as equivalent to "pulling a rabbit out of a hat" (Edwards 2015c). Two 6-month study periods were claimed to be necessary (Edwards 2015c).

The problems added up to a perfect storm of corrosive water, lack of corrosion control, and nonconservative water testing that failed to either detect or report the corrosion, and they were compounded by a classic series of calamity-related behaviors, described below (DemocracyNow! 2016; Eclectablog 2015; Erb 2015a; Hulett 2015).

Characteristics of Corrosion-Related Calamities

What happened in Flint is typical of corrosion-related calamities such as those associated with Chinese drywall (CDW) and the San Francisco–Oakland Bay Bridge (SFOBB).

In the CDW case, the purchase order for the Taishan drywall company's product was reissued after removal of the requirement to meet an ASTM standard of lower sulfur levels after Taishan reported that it could not meet the standard (Fallon and Wilkinson 2010). In the SFOBB case, standards and journal papers warned of hydrogen embrittlement of high-strength zinc-coated alloys in water but were not heeded (Gorman et al. 2015). In all three cases, the calamity could be traced to fatal decisions in design, improper materials selection, failure to adhere to standards, denial or failure to recognize emerging problems, and missed opportunities to implement midcourse corrections.

Moreover, corrosion immunity is assumed or misunderstood (Scully 2015), and when a problem starts to become apparent, it is often met with denial that corrosion happens (Eclectablog 2015; Erb 2015b; Hulett 2015; Smith 2015), a focus on issues other than the root cause (Carmody 2015; Fonger 2014a), criticism of the whistleblowers who report corrosion or its consequences, misplaced emphasis on assigning blame instead of making improvements, begrudging and late admission of corrosion problems and recognition of the real cause, scapegoating of select individuals, and reactionary emergency funding, which often is not adequate and quickly evaporates (figure 1).

[1] In the 1991 Lead and Copper Rule (LCR) the EPA defined a maximum concentration for lead in water at an action level of 0.015 mg/L (15 ppb) (40 USC. Sec 141), although the EPA acknowledges that sampling techniques might "miss the worst case lead concentrations" in water (Edwards et al. 2015).

[2] 1996 Safe Drinking Water Act (SDWA) 42 United States Code (USC) §300f, Section 1417, Prohibition on Use of Lead Pipes, Solder, and Flux, p. 652.

For the authorities and decision makers in Flint, adequate technical information was available about risks associated with lead pipe and water-based corrosion, together with lessons from previous incidents and standards-based guidance, to enable wise, data-based, informed decisions before the problem became a calamity. Yet *almost no opportunity was missed to miss an opportunity* for corrective action.

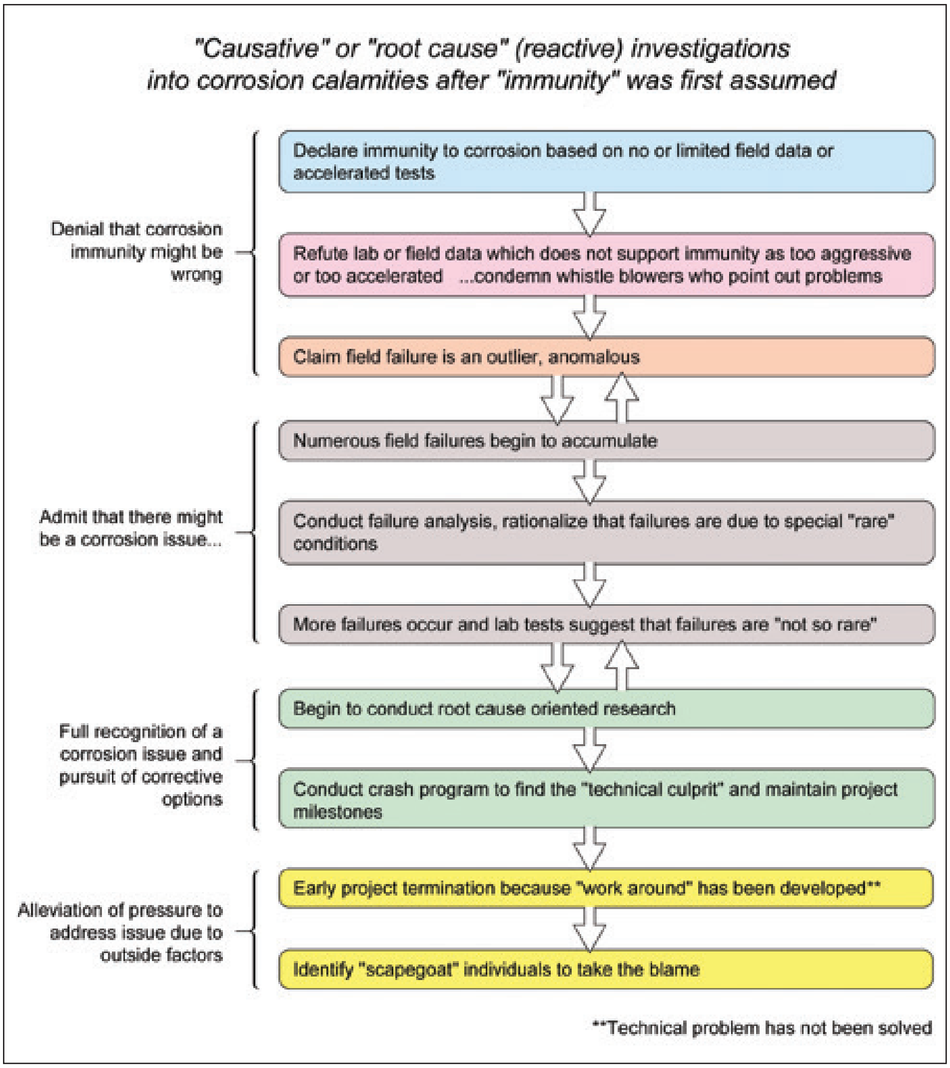

FIGURE 1 Flow chart depicting the stages of doubt and "corrective" actions often encountered during technology stewardship for an engineering problem involving a corrosion-related calamity.

Materials Used in US Public Water Systems

Over a million miles of pipes, treatment plants, water mains, and service lines in the United States connect water sources to points of consumption (e.g., homes, places of business). Pipes may be made of copper (Cu), galvanized steel, cast iron, or plastic (e.g., polyvinyl chloride, high-density polyethylene), but a large number are lead (Pb).

Installation of lead pipes in the United States began in the 1800s and continued into the 1900s in most major cities based on the justification that lead was malleable and lasted longer than cast iron from a corrosion standpoint (Brodeur 1974; Rabin 2008; Troesken 2006). Industry associations lobbied heavily for lead use. Yet concerns about lead in connection with drinking water have been known for centuries (e.g., Brous 1943; Hodge 1981; Troesken 2006). The decision to use lead has been called one of the most serious environmental disasters in US history (Troesken 2006).

Moreover, lead pipe and lead solder are often galvanically coupled to copper and iron piping, and much of the Flint distribution system is old unlined iron (Hu et al. 2012; Winkless 2016). Together with lead-tin solders used to connect pipes and leaded brasses or other copper alloys used in fittings and household fixtures, lead pipes are the main contributor to large amounts of lead contamination in drinking water all over the country (Paige and Covino 1992). A recent report identified almost 2,000 US water systems with lead, affecting up to 6 million people (Young and Nichols 2016).

Unfortunately, partial replacement of lead pipes has no health benefits (Triantafyllidou and Edwards 2011). The "upstream-downstream" transmission sequence of copper (service line) → lead (service line) → copper (pipe to house) after partial replacement can cause long-range deposition corrosion on lead across remaining lead pipes as well as galvanic corrosion of lead where copper and lead are in close proximity (St. Clair et al. 2012). Both can actually accelerate lead release.

Corrosion

The Hidden Threat

Corrosion often involves a time, age, or condition-based dependency that triggers problems down the road. The problems may be a function of poor engineering design, improper materials selection, poor upkeep, improper practice, and/or human error. The controlling factors and effects of corrosion are often hidden from public view and poorly understood.

The long time periods before corrosion problems become evident may lead to a false sense of security for technologists and officials until there is a serious problem. Also because of the long time dependency—and corresponding perception that the risk is not immediate—many managers defer allocation of resources to corrosion problems that cost much more to repair later.

The challenge for managers is an inability to (1) decide which technical issues can be deferred and which cannot, and (2) know what the return on investment will be from intervention before there is a problem.[3] Protection from known corrosion problems therefore often requires reliance on standards or best practices that must be followed faithfully and conservatively even if they are not understood. For this reason management of many complex corrosion issues has been distilled into easy to implement standards and practices, sometimes with justifications cited in the references at the back of such standards.

Lead Corrosion in Water

Lead corrosion is typically anodically controlled and is governed by the insolubility and other attributes of the mineral scales and lead (II) corrosion deposits formed at the lead anode (Smith 1987). Anion content and ionic mobility are key. For example, lead sulfates are relatively insoluble while lead chlorides are soluble. Therefore, the chloride-to-sulfate mass ratio (CSMR) governs the intrinsic corrosion of lead and galvanic corrosion of lead to copper in water (Nguyen et al. 2011).

The lead corrosion rate also depends on the degree of water hardness. Hardness is caused by calcium and magnesium salts, which at levels >125 ppm can lead to the formation of deposits that can limit corrosion (Smith 1987). For soft waters, the lead corrosion rate depends on pH and oxidizers (e.g., O_2, Cl_2) and can be partially mitigated by CO_2 yielding bicarbonates and forming lead (II) carbonates, which also enjoy modest insolubility (Smith 1987). It is often assumed that such scales are good enough to limit lead release.

Figures 2a and b indicate that protection against lead corrosion by formation of Pb(II) carbonate species is ineffective until a pH above 7. Cerussite ($PbCO_3$) and hydrocerussite ($Pb_3(CO_3)_2(OH)_2$) cannot reduce lead levels below 0.020 mg/L (the regulatory maximum) (Boffardi and Sherbondy 1991). Figure 2b shows thermodynamically stable soluble lead species at all pH levels even in the presence of these carbonate films. Lead is not recommended for use for components in soft potable waters (Smith 1987).

Cast iron mains can release iron when waters are corrosive and copper is deposited on iron (Hatch 1955), causing further deposition-induced galvanic corrosion of lead pipe downstream. Plastic pipe eliminates deposition corrosion and galvanic corrosion, but the self-corrosion of any remaining lead pipe in corrosive waters remains an issue (Hu et al. 2012).

Flint River water was 19 times more corrosive than Lake Huron water and contained over 8 times more chloride (Cl^-), which increased the CSMR from 0.45 to 1.6 (Edwards et al. 2015); a CSMR of 0.77 or greater is reported to be highly detrimental (Nguyen et al. 2011). Moreover, the Larson ratio (a measure of iron corrosivity; Larson and Shold 1958) increased from 0.5 to 2.3 upon the switch to Flint River water (Edwards et al. 2015).

One doesn't have to be a corrosion specialist to raise the red flag here, especially when the local automobile manufacturers stopped using Flint River water owing to its corrosive effects on new metal auto parts (Fonger 2014b).

Regulations, Standards, and Research

Standards developed by technical societies and standards-writing organizations represent the consensus guidance of many stakeholders including producers, end users, decision makers, and owners. Standards produced by nonprofit organizations such as the National Association of Corrosion Engineers (NACE International) are designed for the safe use of systems, corrosion control, and public safety.

Other standards and regulations result from government legislation.[4] The 1986 EPA Safe Water Drinking

[3] For discussion of approaches to return on investment, see Koch et al. (2016) and Jacobson (2016).

[4] Materials acceptance standards specify minimum properties for acceptance and should not be confused with those designed to safeguard against materials failures.

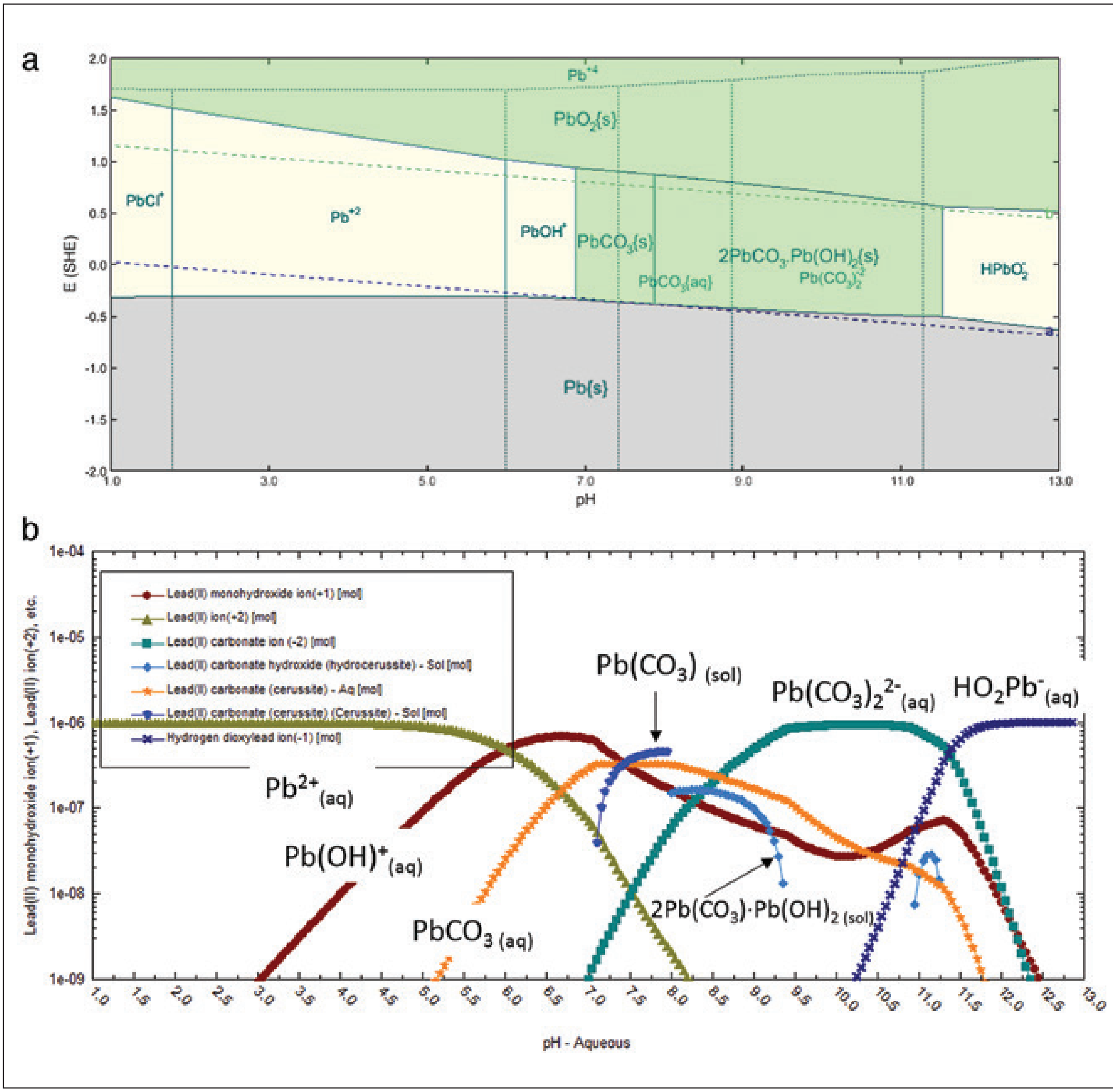

FIGURE 2 **(A)** E-pH equilibrium diagram for the Pb–H_2O system showing the predominance of various lead species in the presence of carbonate. The vertical axis reports the electrochemical potential versus a standard hydrogen electrode (SHE). The horizontal axis is the range of solution pH. Green designates the region of stability of solid Pb oxides or compounds, cream represents the E-pH region for soluble Pb(II) stability, and grey shows the E-pH region for unoxidized Pb or immunity from corrosion. Most drinking water is at a bulk pH of 6–8. It can be seen that lead carbonate hydroxides may only protect over a narrow pH from about 7 to just over 11. During corrosion, Pb anode sites can become acidified to a lower pH. Assuming the pH may decrease from 6–8 to lower levels over time, it can be seen that lead carbonate hydroxides may not be protective to lead at lower pH levels. The conditions for the construction of the diagram were ambient air, [Pb] = 10^{-6} molar, [CO_3^{2-}] = .01 molar, and 25°C. (The equilibrium species depicted are unlikely to exactly represent all the metastable species present in real applications.) **(B)** Lead Pb(II) species stability diagram showing concentrations of various lead species as a function of pH. The vertical axis reports the electrochemical potential versus a standard hydrogen electrode. The horizontal axis is the range of solution pH. The concentrations assumed to construct the diagram were [Pb^{2+}] = 10^{-6} molar; [PO_4^{3-}] = 0 molar; [CO_3^{2-}] = .01 molar; open to the atmosphere. The ionic Pb^{2+} concentration responsible for lead poisoning begins to decrease from very high levels at a pH of approximately 5.5 and falls to low levels at a pH of >8 in the presence of Pb(II) carbonate films. However, some dissolved species, such as $Pb(CO_3)_2^{2-}$, are thermodynamically stable. aq = aqueous or dissolved species; mol = molar; sol = solid.

Act (SWDA) prohibited use of materials that were not lead free. Although the act limits the use of lead pipes, solders, and fixtures in new installation or repair after June 1986, it left in place miles of lead pipe or solder that are vulnerable to corrosive waters and depend on chemical inhibitors.

But standards often are not considered, are misunderstood, or are “gamed” to avoid corrective action. Indeed, adherence to standards may simply seem excessively burdensome when the risks are not known or understood.

In addition to guidance from standards, much can be learned about corrosion problems from published information, new science, and previous experience (Scully 2015). Research on lead corrosion and release and on lead/copper galvanic corrosion issues in freshwater was published well before 2014 (Nguyen et al. 2011). Several notable articles warned of the dangers of lead corrosion and release as a function of water chemistry in fresh water and about the role of water chemistry in triggering lead release (Hu 2012; Nguyen et al. 2011; St. Clair et al. 2015).

Standards must be updated based on new science, but gaps persist in scientific knowledge. For instance, changes in the Pb release rate after complex sequence changes in water chemistry (e.g., intermittent or on/off orthophosphate treatment) are unknown, as are residual release rates under different scales and corrosion products as a function of water chemistry and deposit type (Gerke et al. 2016). Such information is of immense practical importance for the management of water systems with lead pipe.

Water Chemistry and Treatment

Clean water is threatened by natural and anthropogenic factors such as drought, climate change, aging infrastructure, and, more specifically, higher Cl^- content in water due to rising sea levels and the use of road salts. Chloride and other factors also affect the corrosion of public water infrastructure components, further compromising water quality. In addition, the corrosiveness of drinking water sources differs around the world and can change with time, creating the risk that a dormant or low-level corrosion problem can be triggered by seemingly mundane changes in water chemistry (Nguyen et al. 2011; St. Clair et al. 2012).

Water chemistry control and the production of drinking water thus present complex tradeoffs: it is necessary to manage water hardness to prevent flow restrictions due to excessive deposits, remove contaminants by treatments, add chlorine or chloramines to control biological toxins, and add lime or orthophosphates to limit lead corrosion. The efficacy of corrosion control must be monitored carefully.

Disinfectants like chlorine, whose use is justified given that contamination of drinking water can be fatal, are well-known electrochemical oxidants that provide a potent cathodic half-cell reaction that increases the corrosion rate of lead, steel, and copper (Ha et al. 2011; Jones 1996). Instead of recognizing and addressing the corrosion, officials in Flint added chlorination in an attempt to disinfect the water, significantly enhancing corrosion rates. The higher rates of iron corrosion, in turn, consumed the chlorine disinfectant and likely triggered the *Legionella* growth.

The need for orthophosphate as a chemical inhibitor to control lead corrosion is well known (Boffardi and Sherbondy 1991; Ha and Scully 2013). The protection provided by a covering lead orthophosphate film $Pb_3(PO_4)_2$ ranges from about pH 4–6 to 11.5 (figure 3a). However, as the potential pH (figure 3a) and Pb(II) species stability (figure 3b) diagrams indicate, decreased Pb^{2+} thermodynamic stability above pH 4.5 is not equivalent to immunity to lead corrosion. Even when the dominant thermodynamic species over a range of neutral pH is solid $Pb_3(PO_4)_2$, there is still a nonzero equilibrium concentration of aqueous or dissolved Pb^{2+} (shown as Pb^{2+} and $Pb(OH)^+$) from about pH 3.5 to 12.5 (figure 3b) under the conditions explored.

The human tolerance level for lead is now recognized to approach zero (Edwards 2014). Therefore, while some hard waters and lime treatments can “passivate” somewhat (figures 2 and 3), this can hardly be a strategy for public safety. Corrosion inhibitors such as orthophosphate could have dramatically reduced the lead corrosion rate (Boffardi and Sherbondy 1991) in Flint and would reportedly have cost the state of Michigan about $100/day (Gosk et al. 2016). But when the City of Flint switched from Lake Huron to Flint River water, corrosion control with orthophosphate was discontinued despite the river’s greater known corrosivity.

Impact of Government Inquiries and Congressional Hearings

In the awake of calamities, federal hearings are often held to investigate and assess responsibility. But the impacts of these investigative efforts are variable. For example, the hearings and report of the Presidential

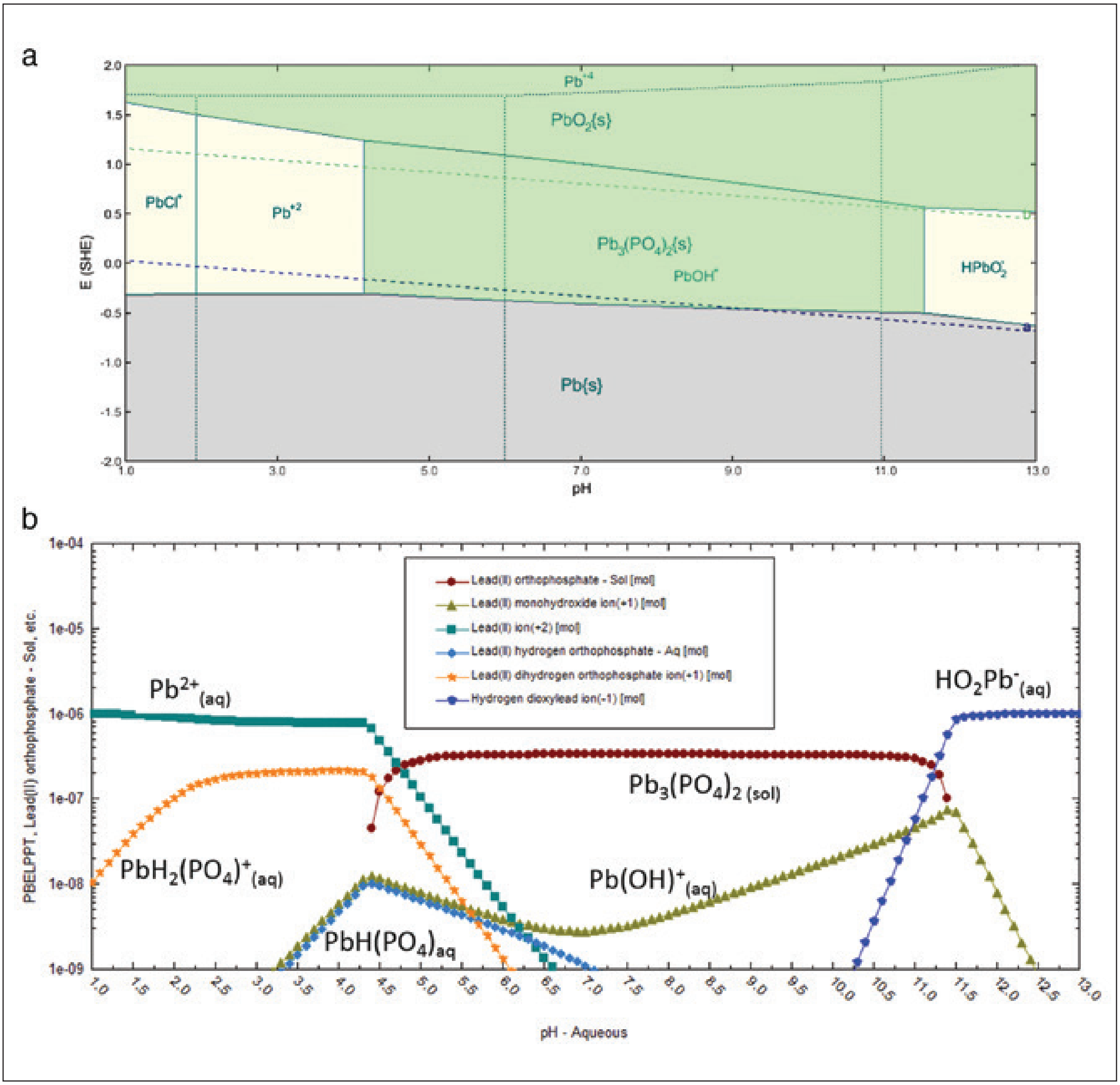

FIGURE 3 **(A)** E-pH equilibrium diagram for the Pb–H_2O system showing the predominance of various lead species in the presence of phosphate. The conditions for the construction of the diagram were ambient air, [Pb^{2+}] = 10^{-6} molar, [PO_4^{3-}] = .01 molar. Green designates the region of stability of solid Pb oxides or compounds, cream represents the E-pH region for soluble Pb(II) stability, and grey shows the E-pH region for unoxidized Pb or immunity from corrosion. Pb(II) phosphates shown in green are protective. (The equilibrium species depicted are unlikely to exactly represent all the metastable species present in real applications.) Most drinking water is at a bulk pH of 6–8, but Pb anode sites can become acidified over time to a lower pH. The Pb(II) phosphates are stable to a lower pH than Pb(II) carbonates. The range of protection by a covering lead orthophosphate film $Pb_3(PO_4)_2$ is about pH 4–11.5, illustrating the benefits of orthophosphate inhibitor over the pH range of 4.5–8 compared to natural carbonates. **(B)** Lead Pb(II) species stability diagram showing concentrations of various lead species as a function of pH. The species concentrations assumed to construct the diagram were [Pb^{2+}] = 10^{-6} molar; [PO_4^{3-}] = .01 molar; [CO_3^{2-}] = 0.0 molar; open to the atmosphere. The ionic Pb^{2+} concentration responsible for lead poisoning begins to decline at a pH above about 4.5 and falls to low levels at a pH of >6.5 in the presence of Pb(II) phosphate films such as lead(II) orthophosphate. This illustrates the benefits of phosphate inhibitor over the pH range of 4.5–8 compared to natural carbonates. However, this treatment only reduces Pb(II) stability, indicating that some soluble lead will be thermodynamically stable even after use of a corrosion inhibitor. aq = aqueous or dissolved species; mol = molar; sol = solid.

Commission on the Space Shuttle *Challenger* Accident[5] in 1986 did not prevent the *Columbia* orbiter disaster in 2003[6] (NASA 2003; Rogers Commission 1986).

Congressional hearings on Flint may be just as ineffective. The issue was immediately politicized: the political right blamed the EPA while the left blamed the state of Michigan. Environmental racism was even suggested (House of Representatives Committee on Oversight and Government Reform 2016).

Why are calamities not averted even after careful review of the root causes, actions taken, and missed opportunities?

Why are calamities not averted even after commissions carefully review the time line, root causes, actions taken, and missed opportunities? Hearings and commission reports do not change the *underlying culture, lack of understanding of risks, and habits* that lead to such calamities. Similarities between a current situation and past experiences are not recognized, time is limited, financial pressures exist, other problems clamor for attention, and complex technologies have massively parallel failure scenarios and many potential root causes.

During the March 2016 House of Representatives Oversight and Government Reform Hearing about the Flint Water Drinking Contamination Issue (2016), Michigan governor Rick Snyder said that the state would "try to learn from this mistake." Indeed, *one of the main lessons from the Flint calamity is that past lessons were not learned.*

[5] The Rogers Commission Report observed that lack of failure after each launch was taken as evidence of 0 percent risk of failure, an approach likened to a game of Russian roulette where each successful orbiter launch gave a false sense of security.

[6] NASA and contractors were said to have unjustified optimism. In its report on the *Columbia* space shuttle disaster the Columbia Accident Investigation Board listed over 1,000 paths in the fault tree analysis conducted after the fact, but noted that 33 foam strikes were dismissed as not critical to flight safety (NASA 2003).

Tools to Avoid Future Corrosion Calamities

The path forward does not likely involve more standards and legislation. Ample evidence indicates the adequacy of standards in many cases, although customized standards may be needed when new technology, knowledge, or complexities emerge.

But technologists and policymakers may be too quick to rule out related standards that could help. Decision makers lack basic corrosion education to know when to seek expert advice. Technologists and public officials lack tools to weigh risks quickly rather than relying on lengthy studies.

Corrosion education is part of the solution, as identified in a recent study (NRC 2009). Managers can also benefit from a variety of accessible tools and resources that facilitate risk assessment and decision making, as explained in the following sections.

Big Data

One way to anticipate and manage potential corrosion calamities might be to implement the revolution occurring in biomedical data sciences using big data. Data on lead release could be collected in a database of drinking water systems covering a number of materials, water chemistry, corrosion inhibitor use, and physical variables as well as historical factors. Major advances in data integration, fusion, modelling, and analytics might be required. Technologists must be trained in methods to identify important trends in massive amounts of data. What are the common attributes of a water system experiencing high lead levels? Conditions that produce a likelihood of high lead release rates would become evident. A database with such information could be queried by decision makers and technology stewards, and the data could help avoid recurrence of Flint-type issues in other water systems. Reported experiences with lead pipe could yield data on water chemistry factors correlated with high lead releases.[7]

The Flint authorities might have thought that lead levels would decline over time of exposure. But a quick check of the proposed database would have revealed that there was no reasonable hope of a decline in lead levels sufficient to achieve less than 15 ppb given the

[7] Use of big data is the opposite of computer prognosis and deterministic multiscale modelling; in the latter, governing laws and properties are known well enough to take inputs to prediction of lead levels through a quantitative scientific model. In big data the exact deterministic model is not known.

high corrosivity of the Flint River water and the high lead levels seen so far (Edwards 2015c).

Simulation

Another tool would be a simulator game that outputs relative levels of lead release in water infrastructure (e.g., supply, treatment, plant, pump, distribution line, service line) under various scenarios. The simulation could also feature other parallel failure scenarios such as biotoxin release due to lack of disinfection.

The purpose is to illuminate sensitivities to various decisions and the risks (or consequences) of various actions (or inaction) by reporting the impacts of various scenarios. The player selects combinations of lead, copper, iron, and plastic pipe, and also picks water chemistries, disinfectants, and corrosion inhibitors. The resulting game gives a running concentration of lead and levels of biotoxins as a function of each factor. For instance, "superchlorination" might disinfect but lead release would become intolerable due to accelerated corrosion.

A similar tool to recognize the dangers of corrosion is *CorrSimulator* (Greenwood 2012), a DOD-funded online corrosion game in which the player acts as a plant manager to make corrosion-related decisions that have an impact on equipment operation and longevity. Even at this very simplistic stage such a lead risk assessment game is useful and important enough to be distributed to thousands of water utility managers. For example, the effects of the orthophosphate inhibitor would be immediately clear if programmed into the game. Technologists and policymakers could use these tools to anticipate and manage potential risks.

Systemic Sampling vs. Real-Time Online Sensing

Cyberphysical systems are another new technology that could help. There is much uncertainty and error in manual lead sampling. Such sampling could be automated with thousands of lead sensors at many points in a water system as part of a smart cities initiative. Data would ideally be acquired by computers and sent to decision makers. Why wait for a 6-month study via batch analysis of lead concentration? Sample in real time, send wireless data, and observe the downstream consequences of actions in upstream water management.

Progress is required in sensing, communication, energy harvesting, low-power electronics, and data analysis.

Financial Management

Corrosion management financial tools (perhaps with a health assessment or public safety risk calculator) are desperately needed so that a compelling case can be made about the benefits of corrosion control (Jacobson 2016; Koch et al. 2016).

With these tools, beleaguered technologists and policymakers might be able to make a more compelling argument to decision makers in a timely manner about the need for corrosion control so that action can be taken and calamities averted.

Acknowledgments

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The IMPACT study presents corrosion control strategies that could save hundreds of billions of dollars per year.

NACE International's IMPACT Study Breaks New Ground in Corrosion Management Research and Practice

Gretchen A. Jacobson

Gretchen A. Jacobson is managing editor, Materials Performance, NACE International.

In 2002 the US Federal Highway Administration (FHWA) released a benchmark study, *Corrosion Costs and Preventive Strategies in the United States* (Koch et al. 2002), on costs associated with metallic corrosion in a wide range of industries. It revealed that the total annual estimated direct cost of corrosion was $276 billion, equivalent to 3.1 percent of the US gross domestic product (GDP). In addition to detailed cost analyses, the report presented preventive corrosion control strategies.

The study, updated to account for inflation, is still widely used, but there had been no attempt at a more in-depth look at the effects of corrosion as related to corrosion management practices, particularly on a global basis. In October 2014 NACE International, the technical society for corrosion professionals with more than 36,000 members worldwide, initiated the International Measures of Prevention, Application, and Economics of Corrosion Technologies (IMPACT) study. The results were released in March 2016 at the NACE annual conference, CORROSION 2016, in Vancouver, and the report (Koch et al. 2016) is available at impact.nace.org.

This article provides a summary of the scope, approach, and significant findings of the IMPACT study, including corrosion control strategies that could save hundreds of billions of dollars per year.

Scope of IMPACT

A primary goal of IMPACT was to examine the role of corrosion management in establishing industry best practices, enabling maximum cost savings, enhancing public safety, and ensuring environmental protection. The study focuses on segments of four major industries—energy, utilities, transportation, and infrastructure—and features in-depth research and resources in the following areas:

- Updates of the global cost of corrosion
- Assessment of corrosion management practices across various industries and geographies
- A template for corrosion management in the form of a corrosion management system framework and guidelines
- Financial tools that can be used for calculating life cycle costs and return on investment
- Methods for organizations to benchmark their corrosion management programs with others around the world.

Update of the Global Cost of Corrosion

To determine the global cost of corrosion, IMPACT researchers analyzed publicly available studies from around the world. The assessment (included in the report) revealed that the global cost is now an astounding $2.5 trillion, equating to 3.4 percent of a country's GDP.

The use of corrosion control practices could yield savings of 15–35 percent—between $375 and $875 billion. These costs typically do not include the safety or environmental impacts of corrosion, which can have significant financial, regulatory, and legal consequences for an organization.

Time-proven methods for preventing and controlling corrosion depend on the specific material to be protected; environmental aspects such as soil resistivity, humidity, and exposure to saltwater or industrial environments; the type of product to be processed or transported; and many other factors. The most commonly used methods are organic and metallic protective coatings; corrosion-resistant alloys, plastics, and polymers; corrosion inhibitors; and cathodic protection.[1]

[1] Cathodic protection is a technique used on pipelines, underground storage tanks, and offshore structures that creates an electrochemical cell in which the surface to be protected is the cathode and corrosion reactions are mitigated.

The most critical finding of the IMPACT study is that, while it is important to continue investment in technology and systems for corrosion control, it is essential to put this technology in an organizational management system context and justify corrosion control actions by business impact. This can be accomplished through a corrosion management system that is understood and supported at every level of an organization involved in protecting assets. The Corrosion Management System Framework is the core deliverable of the IMPACT study.

Safety and environmental impacts of corrosion can have significant financial, regulatory, and legal consequences for an organization.

The Corrosion Management System Framework

The Corrosion Management System (CMS) Framework is an organizational structure that enables effective corrosion mitigation while providing a positive return on investment (ROI; the benefit, or return, of an investment divided by its cost). The CMS is a set of processes and procedures for planning, executing, and continually improving a company's ability to manage the threat of corrosion for existing and future assets and asset systems. Figure 1 shows the interrelation of a pipeline operator's corrosion management and overall organization management systems. Figure 2 presents the CMS pyramid, which is central to the IMPACT findings and recommendations.

Managing the threat of corrosion requires consideration of both the likelihood and the consequences of corrosion events. The report defines the consequence, or impact, of corrosion as the potential or actual monetary loss associated with the safety or integrity of the corrosion event. This value is typically quantifiable by considering lost revenue, cost of repairs, and cleanup costs, as applicable. Another impact is deterioration of an asset to the point that it is no longer fit for its intended purpose (e.g., lost future production).

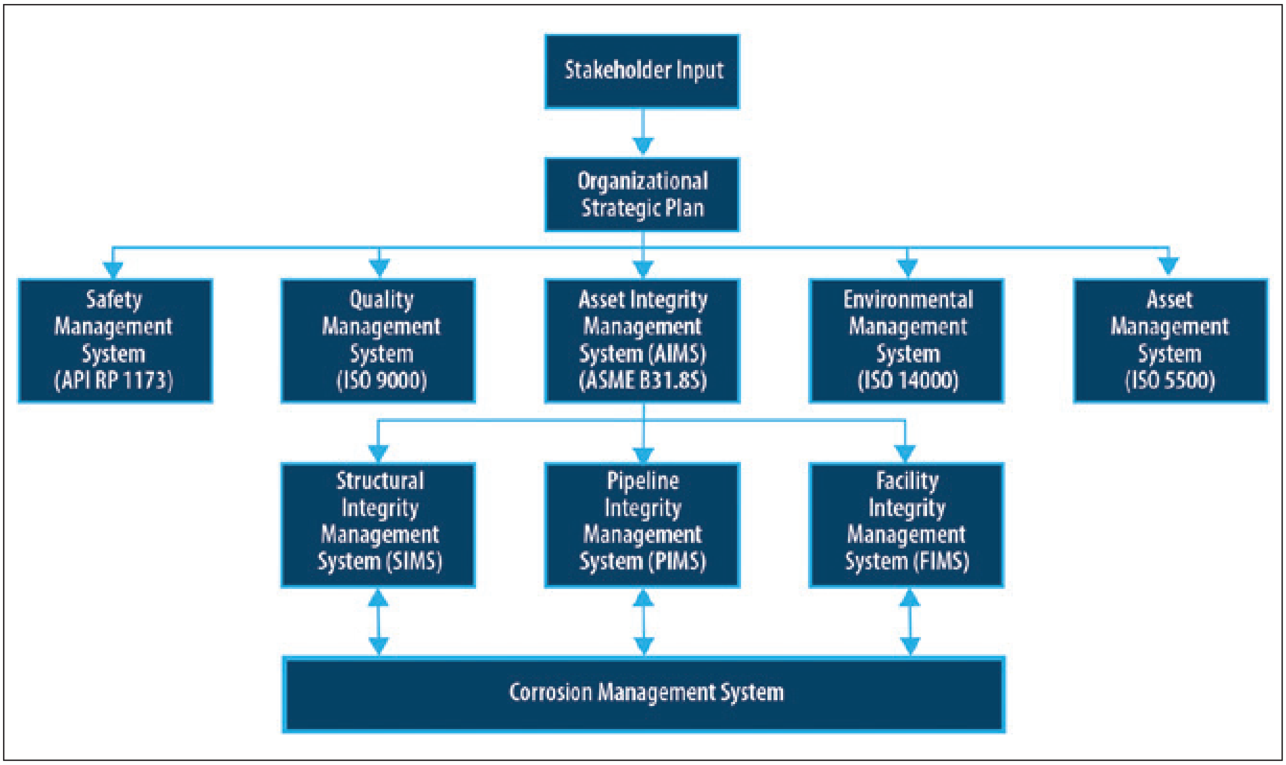

FIGURE 1 Interrelation of an organization management system. This example is for a pipeline operating company. API RP = American Petroleum Institute Recommended Practice; ASME = American Society of Mechanical Engineers; ISO = International Organization for Standardization. Reprinted with permission from NACE International (2016).

In general, corrosion threats should be mitigated to a point where the expenditure of resources is balanced against the benefits gained. To determine whether a corrosion management investment is appropriate, it can be compared to the potential corrosion consequence through an ROI analysis. For corrosion management, the costs may include inspection and other maintenance costs. The ROI is not in capital gains but in the avoidance of safety or integrity costs.

Investing in CMS activities such as inspections and maintenance may not prevent all corrosion events because the likelihood of failure is rarely zero. Additionally, the consequences of corrosion events may be compounded by system-related issues such as lack of training, failure to follow procedures, or inadequate emergency response. Therefore, investing in a CMS to frame corrosion activities with the system elements necessary for planning, execution, and continual improvement should be considered part of the ROI.

The IMPACT report provides diagrams that depict CMS components, as well as information on CMS policies, strategies, and objectives; enablers, controls, and measures; risk management; and many other resources to enable companies to incorporate an effective CMS in their organizational structure.

Benchmarking

A critical component of the IMPACT study was to collect data on how organizations in different industries and countries conduct their corrosion control activities, with emphasis on corrosion management practices and their place in an overall organization's management system.

First, a Corrosion Management Practice Model (CMPM) was developed to provide a repeatable framework for assessing the structure, approach, and features of an organization's CMS. From there, a 70-question self-assessment survey was developed, encompassing nine management system domains: (1) policy, including strategy and objectives, (2) stakeholder integration, (3) organization, (4) accountability, (5) resources, (6) communication, (7) corrosion management practice (CMP) integration, (8) continuous improvement, and (9) performance measures.

Scores for each of these practices ranged from 0 to 1: 0 reflected no capability and 1 the highest level of

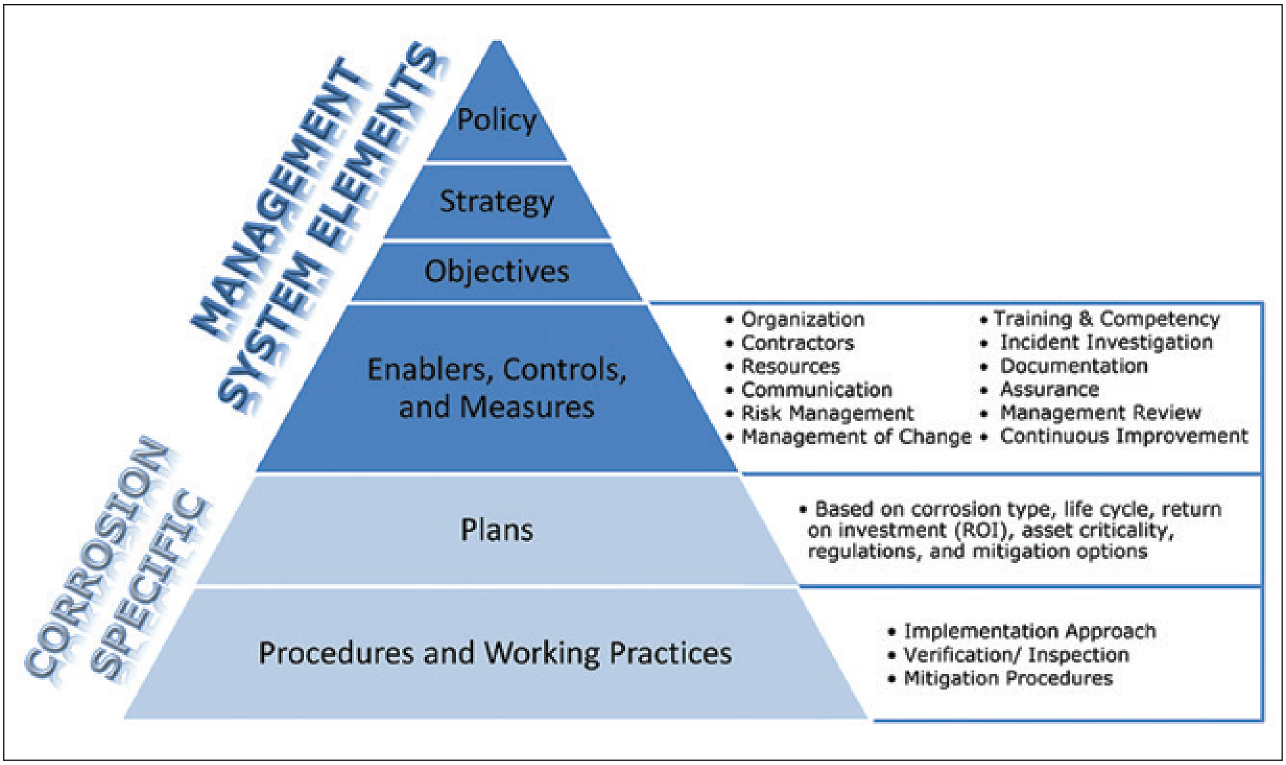

FIGURE 2 The Corrosion Management System (CMS) pyramid: Hierarchy of general and corrosion-specific management elements. Reprinted with permission from NACE International (2016).

capability based on the provided answer options. Table 1 gives an example of a survey question and answer set.

The survey was conducted in industries worldwide spanning aerospace and aviation, chemical, petrochemical, oil and gas, and water and wastewater. In addition, focus groups of personnel at various management and technical levels were organized in several industries and countries to provide further insight into their corrosion management philosophies and practices.

After data collection the study team performed a series of analyses, two of which included comparisons across geographical regions and industries, to develop the observations and recommendations detailed in the IMPACT report.

TABLE 1 Example survey question and answer set

Practice from CMPM	The corrosion management strategy is linked to organization strategy.
Survey question	Is your corrosion management strategy linked to your organization's overall strategy?
Answer options	a) No b) Yes, but to technical requirements only c) Yes, but to business performance only d) Yes, comprehensively
Scoring	Scoring ranges from 0 (baseline) to 1 (best practice) a) 0 b) 0.5* c) 0.5* d) 1.0

CMPM = Corrosion Management Practice Model.
* Weighting of intermediate answers can vary depending on the question and options.

Companies across geographic regions and industries consistently scored lowest on policy and performance measures, and to some extent organization and stakeholder integration. The researchers explain that

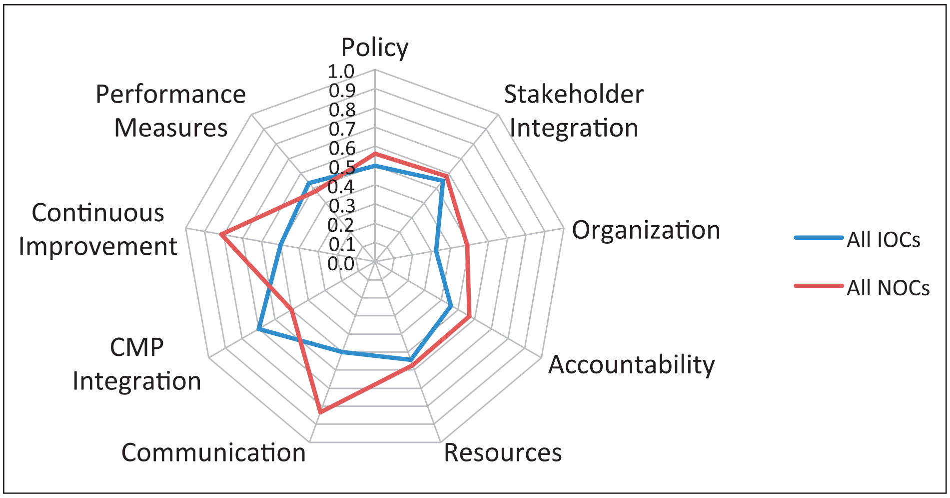

FIGURE 3 Benchmarking of international oil companies (IOCs) and national oil companies (NOCs) on the corrosion management system domains. A score of 1.0 denotes the highest level of performance. CMP = corrosion management practice. Reprinted with permission from NACE International (2016).

corrosion technology is addressed in plans, procedures, and working practices, but not normally incorporated in higher management system domains. Corrosion management should incorporate technology as the foundation of a CMS.

Company personnel can take the survey on the IMPACT website and pull up graphs depicting their corrosion management program results compared to others in their industry, geographic region, or overall. Of particular value would be for personnel at various levels in an organization to take the survey and compare results with one another to determine whether there is alignment—or identify gaps in their knowledge and approach to corrosion management.

Assessment of Corrosion Management Practices by Industry/Sector

The results of the survey and the focus group discussions with industry subject-matter experts (SMEs) demonstrated that corrosion management practices vary significantly based on the type of industry, geography, and organizational culture, from the absence of corrosion management to full incorporation of a CMS into an organization's management system. Even within an organization, significant differences can exist, depending on local culture and practices.

The researchers analyzed the survey results to identify standard and best practices and gaps in corrosion management practices, and recommended mitigation measures for improvement. The study focused on the oil and gas, pipeline, and drinking and wastewater industries, where corrosion has a major impact on safety, the environment, cost of operations, and reputation. The study also reviewed corrosion management practices in the US Department of Defense (DOD).

Oil and Gas Industry

The oil and gas industry is capital-intensive, with assets such as wells, risers, drilling rigs, and offshore platforms in the upstream segment, and pipelines, liquefied natural gas terminals, and refineries in the mid- and downstream segments. Corrosion is a major cost in the operation of oil and gas facilities and most companies have some sort of corrosion control or management program, the complexity of which depends on the size, geographic location, and culture of the organization.

The survey captured self-assessment results from international and national oil companies (IOCs, NOCs) as well as those specializing in intermediate and unconventional oil. Figure 3 is a radar diagram benchmarking the three NOCs and two IOCs that responded to the survey.

Pipelines

Corrosion is a major contributing facture to pipeline failures because of the corrosive nature of their contents, which include dry gas, wet gas, crude oil with entrained/emulsified water, and processed liquids. Appropriate corrosion control technologies and strict monitoring are required to protect these assets, and should be incorporated in a CMS.

One benchmarking effort considered selected onshore pipeline operators in the United States, Canada, and India to discern differences in corrosion management for companies that operate under different regulatory environments (figure 4). The US and Canadian pipeline companies operate under strict national regulations set by the Pipeline and Hazardous Materials Safety Administration and National Energy Board, respectively, whereas the Indian company follows company standards and regulations largely based on internal/local standards and recommended practices. Notwithstanding these differences, all three show similar scores on performance measures, CMP integration, and accountability, and low scores for policy and performance measures.

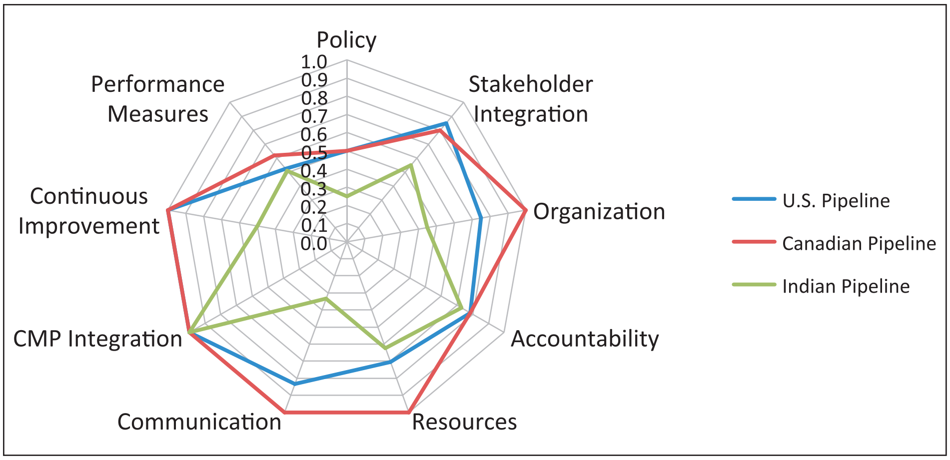

FIGURE 4 Benchmarking of US, Canadian, and Indian onshore pipeline companies. A score of 1.0 denotes the highest level of performance. CMP = corrosion management practice. Reprinted with permission from NACE International (2016).

Drinking and Wastewater Industry

Much of the world's drinking water infrastructure, with millions of miles of pipe, is nearing the end of its useful life. For example, nearly 170,000 public drinking water systems are located across the United States, and there are an estimated 240,000 water main breaks per year, most of them caused by corrosion.

Failures in drinking water infrastructure result in water disruptions, impediments to emergency response, health issues, and damage to other types of infrastructure, such as roadways. Unscheduled repair work to address emergency pipe failures may cause additional disruptions to transportation and commerce.

In 2012 the American Water Works Association determined that the aggregate replacement value for more than 1 million miles of pipes in the United States was approximately $2.1 trillion if all pipes were to be replaced at once. Since not all pipes need to be replaced immediately, it is estimated that the most urgent investments could be spread over 25 years at a cost of approximately $1 trillion.

Capital investment needs for the US wastewater and stormwater systems are estimated to total $298 billion over the next 20 years. Pipes account for three quarters of these needs.

IMPACT considered a report from Australia's National Water Commission (2010) that recorded and measured up to 117 indicators from 73 water utilities across the country serving approximately 75 percent of the population. These indicators (and other information) were examined to determine costs associated with corrosion in the following categories:

- Water loss from pipeline failures
- Intangible costs associated with water and sewer pipe failures and replacement
- Water pipeline corrosion repairs
- Sewage treatment costs due to infiltration
- Capital cost for water and sewer pipeline replacements
- Maintenance and repair of water treatment plants
- Maintenance and repair of other assets such as tanks and pump stations
- Maintenance and repair of sewage treatment plants.

The total annual costs of corrosion in Australia in 2010 were estimated to be $690 million.[2]

Comparison of corrosion management practices of potable water systems in North America and Australia shows that the Australian water companies scored much higher than the North American water industry in continuous improvement, CMP integration, and communication (figure 5). The IMPACT research team found this somewhat surprising considering that the Australian water industry scored low on policy, suggesting that the industry has a limited corrosion management policy, which is considered critical to good corrosion management practices. The American water industry appears to have policies, but implementation can be improved.

US Department of Defense

Since the 2002 FHWA study, which estimated the cost of corrosion to DOD at approximately $20 billion (validated through DOD's own analyses), the DOD has been

[2] Here and throughout, all amounts are in US dollars.

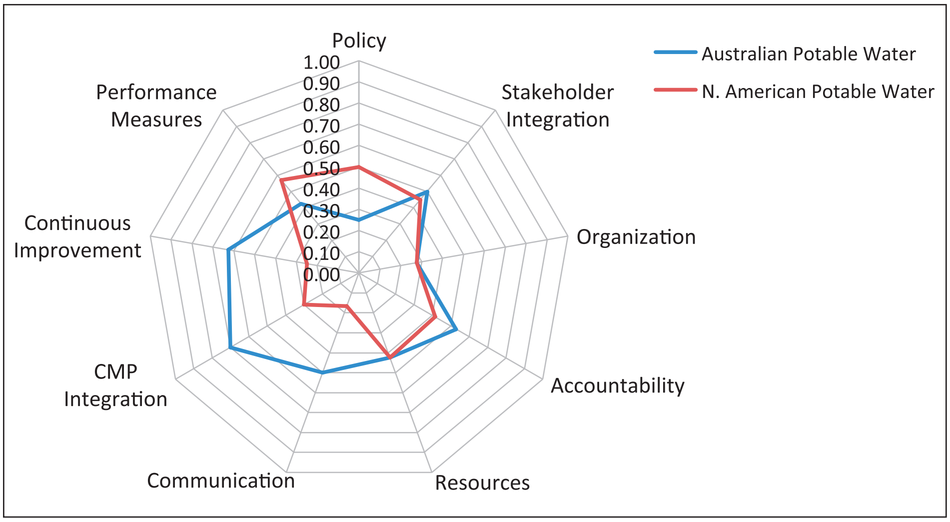

FIGURE 5 Comparison of corrosion management practices of potable water systems in Australia and North America. A score of 1.00 denotes the highest level of performance. CMP = corrosion management practice. Reprinted with permission from NACE International (2016).

developing and implementing a comprehensive corrosion management program.

The IMPACT study stresses the importance of top-down support for a CMS, which is epitomized by the DOD's program. The Under Secretary of Defense for Acquisition, Technology, and Logistics was a supporter from the start. The program, which ranges from setting policy to calculating the cost of corrosion for projects, assets, and components, is run by the DOD Corrosion Policy and Oversight (CPO) Office and includes all critical components of a CMS.

The IMPACT report reviews the CPO's strategic plan and organizational structure and describes how it is successfully managing corrosion control activities across all of the services. The DOD estimates its composite ROI for protecting assets (vehicles, aircraft, base facilities, and weaponry) to be 16:1. An appendix in the report features numerous examples of DOD ROI calculations and the cost of corrosion for projects across all areas.

Corrosion Management Financial Tools

Corrosion management includes all activities, through the lifetime of a structure, to prevent corrosion, repair its damage, and replace the asset. These activities—maintenance, inspection, repair, and removal—are performed at different times during the lifetime of the structure.

Some maintenance is a regular activity (characterized by annual cost), inspections are periodic, and repair is done as warranted. Rehabilitation may be done once or twice during the lifetime, and the cost is usually high. Applying different corrosion management methods may positively affect the lifetime of a structure of a particular design without increasing the cost.

To meet corrosion management objectives, tools or methods are available to calculate the cost of corrosion over part or all of an asset's lifetime. In addition to ROI assessment, these methods include cost adding, constraint or maintenance optimization, and life cycle costing; all are thoroughly described in the IMPACT report, with assistance and tools for integration in a company's CMS.

Return on Investment

ROI is a primary performance measure used to evaluate the efficiency of an investment (or project) or to compare the efficiency of different investments. An ROI calculation is used along with other approaches to develop a business case for a given proposal. The complex part of ROI is determining cost savings and investment costs. To compare investment proposals, ROI must be annualized or the time over which the ROI is achieved must be stated.

Cost Adding

This method, used by the DOD, calculates the cost of corrosion of an asset or project from the top down (i.e., cost of materials, services, or labor required for the project, typically budgeted by upper management). Programs, projects, and assets are analyzed to determine cost components that are specifically related to corrosion, excluding all others. However, significant gaps usually remain, and these are addressed by looking from the bottom up (i.e., considering input from program-implementing employees on the wisest use of funds). All corrosion-related expenditures are added and compared with the top-down cost assessment.

By comparing the top-down and bottom-up corrosion cost assessments, the DOD has been able to accurately determine direct corrosion costs of a project or asset and to calculate ROI.

Constraint Optimization

A constraint optimization framework is used to determine the optimal corrosion management practice for a specific structure or facility in keeping with a fixed or limited budget. Development of the constraint optimization framework requires three major steps:

1. optimizing expenditures of the structure,
2. maximizing the service level subject to budget constraints, and
3. building a constraint optimization model.

Maintenance Optimization

Maintenance optimization calculates the financial benefit of a maintenance action (i.e., inspect, repair, or replace). When expressed in terms of net present value, the scheduling of maintenance projects can also be optimized. One way to monetize corrosion maintenance decisions is through an assessment of risk, which combines probability of failure and its consequence and can be expressed as a cost.

Life Cycle Costing

Life cycle costing (LCC) is used to determine the corrosion cost of certain assets by examining

- capital cost (CAPEX),
- operating and maintenance cost (OPEX),
- indirect cost caused by equipment failure,
- material residual value,
- lost use of asset (i.e., opportunity cost), and
- any other indirect cost, such as damage to people, the environment, and structures as a result of failure.

The LCC approach makes it possible to compare alternatives by quantifying a long-term outlook and determining the ROI. LCC can be performed by using several costing methods, such as cost adding or the Bayesian network approach.

Education and Training

In the next decade a significant transition and turnover in knowledge will occur in the corrosion community. IMPACT cites workforce studies estimating that approximately 25 percent of the total workforce in the United States is over 50 years old, and the median age of NACE members is 47.

While taking advantage of formal internal and external education and training (E&T) programs, corrosion management systems must have a way to effectively transfer individual and institutional knowledge. Specific on-the-job training and mentoring programs are being used to transfer SME knowledge.

From the report it is apparent that E&T course content is heavily focused on the lower levels of the CMS pyramid, procedures and working practices, with essentially no content on the upper levels of policy, strategy, and objectives. Yet E&T will play an important role in the integration of corrosion management in an organization's management system.

Education and training programs must prepare corrosion experts to better communicate to those outside the profession.

E&T programs must also prepare corrosion professionals to better communicate to those outside the profession. They should not expect outsiders to learn their technical language.

Finally, corrosion professional societies must emphasize business strategy and/or public policy when advocating positions to those outside the corrosion profession. Using the principles of a CMS will make these arguments more persuasive.

Strategies for Successful Corrosion Management

Realizing the maximum benefit in reducing corrosion costs (both direct and consequential) requires more than technology; it requires integrating corrosion decisions and practices in an organizational management system. This is enabled by integrating a CMS in system elements that range from corrosion-specific procedures and practices up through organizational policy and strategy—i.e., all levels of the CMS pyramid.

It is essential that traditional corrosion management procedures and practices (lower levels of the pyramid) be communicated to policymakers and decision makers (higher levels of the pyramid) in the form and terminologies of organizational policies. Simply, corrosion management practices need to be translated into the language of the broader organization, which must commit to ownership of the CMS activities and processes. This means buy-in at all levels of an organization.

IMPACT provides tools and examples to help facilitate business communications between corrosion professionals and senior management, leading to integration of a CMS throughout an organization's management system. The US DOD is an excellent example of an organization that effected a cultural change and a commitment to optimization that permitted corrosion management practices to be institutionalized in an entity of its size and diversity.

Industries and governments worldwide will benefit by studying and implementing the findings from the IMPACT study detailed in the publicly available report.

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Transition to a direct charging mechanism for highway use can help to ensure a stable revenue stream.

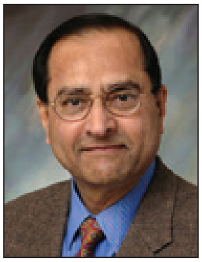
Charging Mechanisms for Road Use

An Interface between Engineering and Public Policy

Bismark R. Agbelie, Samuel Labi, and Kumares C. Sinha


Bismark R. Agbelie


Samuel Labi


Kumares C. Sinha

Increasing numbers of roads and bridges in unsatisfactory condition, along with shrinking funds for maintenance and repair, are of great national concern. For decades, the motor fuel tax, an indirect excise tax on the sale of fuel, has been the primary source of federal and state highway revenue in the United States. The current federal tax on gasoline and diesel is 18.4 and 24.4 cents per gallon, respectively, while the state fuel tax varies by state, averaging about 30 cents per gallon for gasoline and diesel.

Federal and most state fuel tax rates have not changed for many years, and increasing fuel efficiency has created a serious funding gap that is rapidly increasing (NSTIFC 2009; TRB 2006). The American Society of Civil Engineers (ASCE) estimates that to improve the nation's highways,

Bismark R. Agbelie is a postdoctoral research fellow, Samuel Labi is an associate professor of civil engineering, and Kumares C. Sinha (NAE) is Edgar B. and Hedwig M. Olson Distinguished Professor of Civil Engineering, all at Purdue University.

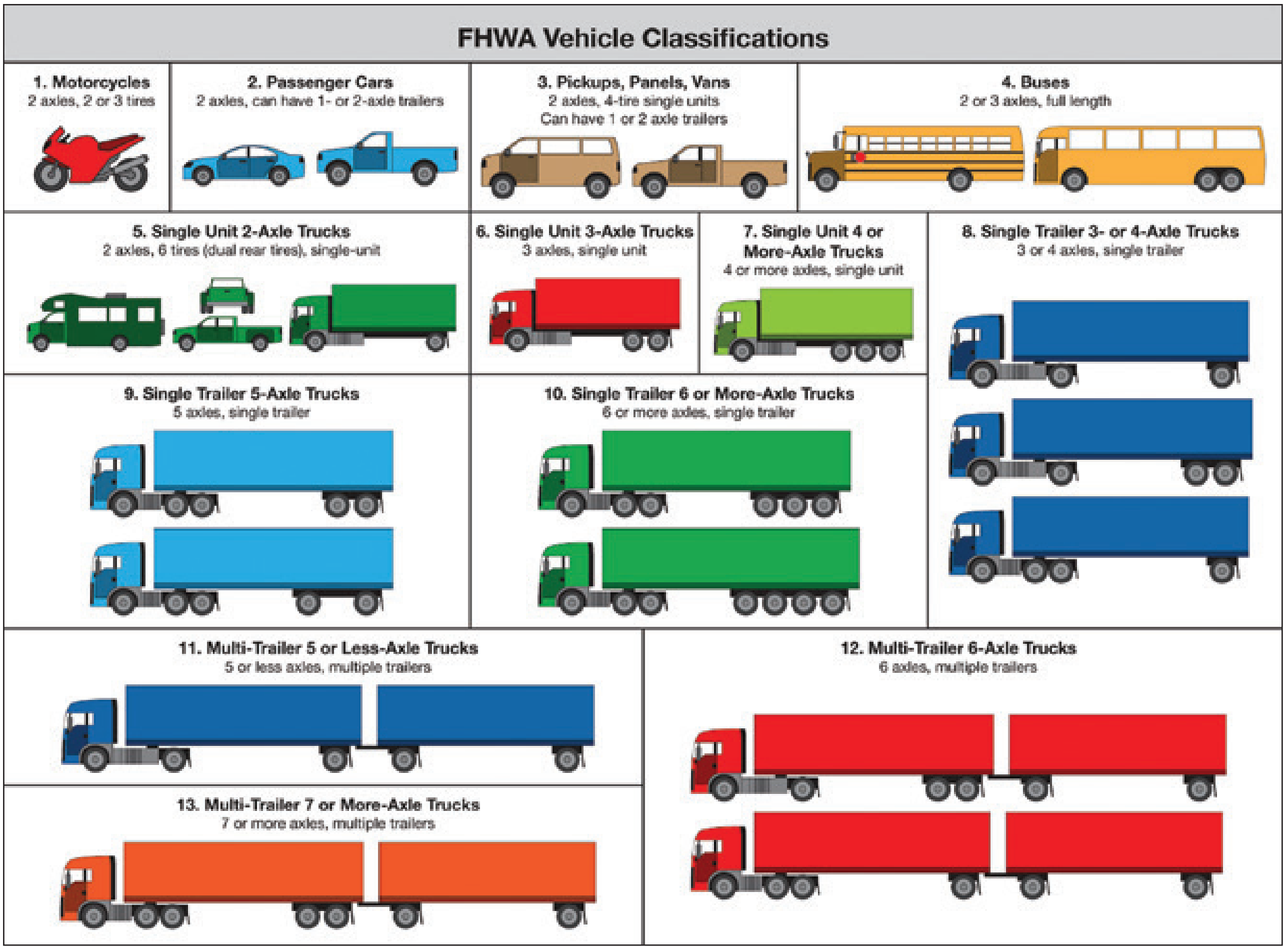


FIGURE 1 Federal Highway Administration (FHWA) 13-category vehicle classification. Reprinted with permission from Randall (2012).

$170 billion needs to be invested annually—$79 billion more than the $91 billion that is currently spent. The effect of this shortfall is deferment in highway capital investments, resulting in a cycle of maintenance cutbacks, further deterioration, and increased need for repair. If present trends continue, the gap in highway funding—48 percent of the total need in 2010—can be expected to grow to 54 percent by 2040 (ASCE 2013).

It is important to recognize the significance of the dichotomy between expenditures and needs. An agency can only spend the resources it has; but the actual need often far exceeds what is actually spent.

Why the Fuel Tax Is Inadequate

Although the fuel tax–based funding mechanism worked well for most of the 20th century, it is now anachronistic and even counterproductive for several reasons.

1. Because the revenue from the tax depends on the amount of fuel consumed and because the federal formula rewards highway agencies for higher miles of travel in their state, this mechanism does not promote travel reduction or fuel conservation. In effect, it contributes to the emission of greenhouse gases and other air pollutants, impacts that are directly related to fuel consumption.
2. The increasing use of hybrid and electric vehicles makes the concept of fuel tax inconsistent with revenue generation objectives.
3. The current fuel tax is not equitable across highway user groups (vehicle classes): although higher vehicle classes (trucks) consume more fuel per unit of travel—and thus pay more in fuel taxes—compared to lower classes (automobiles), the damage a truck inflicts on the infrastructure compared to an automobile far exceeds the extra amount of fuel a truck consumes compared to an automobile.

Alternatives

Possible ways to address the inadequacy of the existing pricing mechanism might be to increase the fuel tax rate or index the fuel tax to inflation at the federal and state levels, charge tolls on specific road corridors, increase state vehicle registration fees, adopt other local taxes specifically for transportation, impose a sales tax (at any level of government), or increase the local property tax. These approaches could be used individually or in combination. However, even if they were politically palatable, these approaches do not adequately address the core concerns associated with the existing mechanism of highway financing.

The time has come to transition from the current indirect mechanism of road user charging to a direct mechanism. This need has been recognized for some time but it is only recently that the implementation of a direct mechanism has become technically and economically feasible. With direct user charging (DUC), the cost responsibilities of each vehicle class can be used as a guide to charge individual vehicles. This approach requires a detailed allocation of highway costs, the steps for which are discussed in the next section.

Cost Responsibilities by Road User/Vehicle Class

Road User/Vehicle Classes

The Federal Highway Administration (FHWA) vehicle classification scheme represents the vehicles that operate on highways and categorizes road user groups based on vehicle type, size, and number of axles (figure 1). Heavier vehicles are further classified in terms of their maximum gross weight.

The physical degradation of pavements and bridges is linked directly to vehicle weights and axle distributions, and operational degradation (in terms of safety and mobility) is affected by vehicle size. For example, engineering principles indicate that doubling the traffic load causes an eightfold increase in pavement damage. Similar nonlinearity is evident in the structural damage to bridges when subjected to traffic loading.

Highway System Use by User/Vehicle Class

Highway system use is generally quantified in terms of vehicle-miles travelled (VMT), and user charging is based on the extent to which each class uses the highway. The national VMT in 2013 was 3.04 trillion (FHWA 2015). The distribution by vehicle class for the state of Indiana is shown in figure 2. Passenger vehicles accounted for the greatest amount of road use (63 percent), followed by vans and pickup trucks (25 percent). Tractor-trailer trucks (classes 8–13) accounted for just 8 percent of highway use, but they cause the greatest damage to pavements and bridges.

Where the costs cannot be attributed to specific vehicle classes and thus are considered common costs across all vehicle classes, equal VMT fees can be applied, and where the costs are allocated differently across vehicle classes due to vehicle weight or size differences, the VMT fees need to be modified to reflect the extra pavement thickness and extra strength of bridge components required to support heavier vehicles

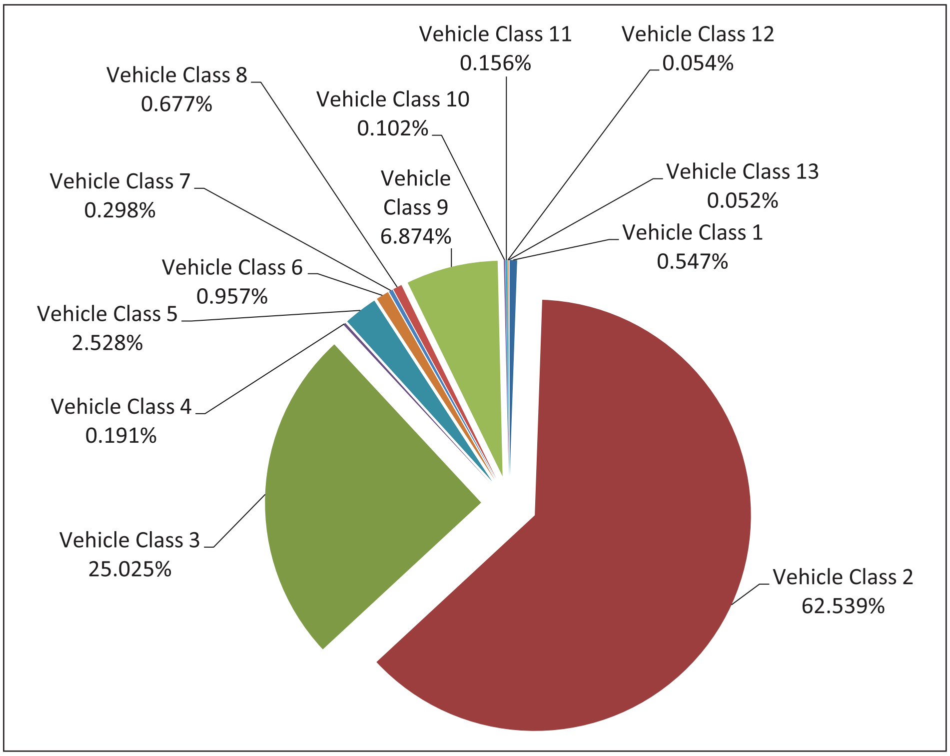


FIGURE 2 Vehicle-miles travelled (VMT) distributions by vehicle class in Indiana. Reprinted with permission from Klatko et al. (2015).

or to reflect the extra roadway width needed to accommodate larger vehicles.

Examples of modified vehicle-miles are load-miles or passenger car equivalent miles (PCE-miles). Load-miles, which are consistent with weight-distance fees, may be measured in ton-miles or equivalent single axle load miles (ESAL-miles). The ESAL concept arose from the need to develop a common denominator for measuring traffic load to account for the different damage contributions of each user group. It is derived from the equivalent wheel load factor (Yoder and Witczak 1975) that is defined by the damage per pass caused to a specific pavement by the vehicle in question relative to the damage per pass caused by a reference vehicle (or axle load).

The American Association of State Highway Officials (AASHO) Road Test in Batavia, Illinois, in late 1950s established the reference axle load as 18,000-lb. single axle with dual tires. A higher ESAL value indicates a relatively higher damage contribution. For a given pavement thickness and material type, ESAL values vary significantly according to the vehicle class (and therefore the number of axles and axle configuration) and loading typically carried by that class in a given state. Table 1 presents the ESAL distribution by vehicle class and pavement material type in Indiana, averaged over all thicknesses. For each class of vehicles, the nature of loadings may vary across the two pavement types according to travel patterns and thus affect the relative ESAL values.

The current trend in pavement design is toward a mechanistic-empirical approach (AASHTO 2015) that calibrates the physical causes of stresses in pavement structures with performance data from the FHWA Long-Term Pavement Performance (LTPP) program or other sources to determine the damage relationships (AASHTO 2010).

TABLE 1 Aggregated equivalent single axle loads (ESALs) by vehicle class in Indiana

	ESALs	
FHWA vehicle class	Rigid pavement	Flexible pavement
1–3	0.000	0.000
4–10	0.230	0.316
11–13	1.115	0.860

FHWA = Federal Highway Administration.
Reprinted with permission from Gulen et al. (2000).

The PCE concept is similar to the ESAL. The rationale is that, from an operational viewpoint, the presence of large vehicles in the traffic stream reduces capacity because these vehicles (1) take up more space, (2) have operating characteristics (acceleration/deceleration) that are inferior to those of passenger cars, thus requiring longer headways, and (3) cause drivers of nearby vehicles to keep longer headways from them. From a physical facility viewpoint, the roadway must be wider to accommodate large vehicles, and this impacts the amount of material, labor, and equipment for the construction. Table 2 presents PCE in Indiana by vehicle class and highway class. According to the PCE shown, a bus (Vehicle Class 4) would be operationally equivalent to 2.2 passenger vehicles for use of any road that is not part of the Interstate Highway System.

TABLE 2 Passenger car equivalents (PCE) by vehicle class and highway class in Indiana

	PCE		
Vehicle class	Interstate	Non-Interstate NHS	Non-NHS
1–3	1	1	1
4–7	1.35	2.2	2.2
8–13	1.6	2.2	2.2

NHS = National Highway System.
Based on data from Ahmed et al. (2011).

Allocation of Costs

Pavement Costs

Costs for new pavement construction can be analyzed on a project-by-project basis and separated into two components: those on a *base facility* (the thinnest pavement adequate to support the lightest class of vehicles), which serves as a platform for building the *remaining facility* (the additional pavement layers needed to support heavier vehicles). The base facility costs are allocated to vehicle classes based on VMT, with adjustments for vehicle width; the remaining-facility costs are typically allocated based on vehicle weight, specifically, ESAL-miles of travel (FHWA 1997).

Costs for pavement maintenance and rehabilitation are incurred based on (1) load, allocated to the vehicle classes on the basis of their ESAL contributions, and (2) nonload (damage due to the environment), allocated to the vehicle classes based on their VMT contributions.

Bridge Infrastructure Costs

Bridge construction is more costly when heavier vehicles must be accommodated, so costs are allocated proportionally by vehicle class because each class induces different stress levels. New bridge construction costs are typically allocated using factors for design loadings established by AASHTO. These factors are typically developed by statistically correlating critical stress levels caused by AASHTO design vehicles and FHWA operating vehicles.

Safety, Mobility, and Other Infrastructure Costs

Most costs of safety, mobility, and other related work are analyzed as common costs and allocated to the user classes on the basis of VMT. A few categories of these costs can be attributed to vehicle size differences and therefore are allocated on the basis of their PCE-weighted VMT (i.e., PCE-miles).

Cost Responsibilities by Vehicle Class

Under current indirect charging mechanisms, the unit cost responsibility values are compared with unit revenue contributions in order to identify inequities among vehicle classes and the fee structure is adjusted accordingly. Table 3 shows the unit cost responsibility values from a recent study in Indiana.

TABLE 3 Cost responsibilities by vehicle class in Indiana

User class	Description	Cost responsibility per VMT
Class 1	Motorcycles	$0.02
Classes 2–3	Automobiles, pickups, vans	$0.02
Classes 4–7	Buses and single-unit trucks	$0.16
Classes 8–10	Single-trailer trucks	$0.12
Classes 11–13	Multitrailer trucks	$0.15

VMT = vehicle-miles travelled.
Based on data from Volovski et al. (2016).

A unit cost value is a ratio of allocated expenditures and the amount of travel; therefore, it is very sensitive to both values. Class 2 vehicles (automobiles) have relatively high amounts of travel compared to other vehicle classes. However, their very low cost responsibility per VMT (as illustrated in table 3) renders the ratio rather modest.

It is also important to note that a large percentage, as high as 50 percent (Luskin et al. 2002), of costs are common costs allocated on the basis of VMT. Cost responsibility values, therefore, cannot be directly translated to specific road user charges and should be used only as a guide to appropriate rates.

Direct User Charging (DUC) to Finance Highway Infrastructure

For the self-financing of highways, with user-based revenues adequate to cover expenditures associated with highway construction, reconstruction, rehabilitation, maintenance, and operations, a user fee structure can be guided by the cost responsibilities of each user class.

The amounts shown in table 3 for vehicle classes 1–3 (2 cents/mile) would help cover only current expenditures, not funding need. To be feasible, the cost allocation process must start with funding needs by work category (construction, reconstruction, rehabilitation, and maintenance) and the amounts adjusted upward to cover the administrative costs as well as costs for implementing the DUC scheme. The user charge amounts will depend on the cost responsibilities of each user class, which in turn depend on the distribution of expenditure levels across work categories over the cost allocation analysis period; if that period was marked by a significant change in spending in certain categories, then the cost responsibilities of various users will also change. For this reason, periodic updates in cost allocation are essential.

In Oregon's 2013 road user charge pilot program (Oregon DOT 2014), which involved only automobile users, participants were billed monthly at a rate of 1.56 cents/mile, an amount that approximates the fuel tax paid by a vehicle with fuel efficiency of 20 miles/gallon plus an administrative fee. The values obtained by a study in Minnesota are 1 cent/mile (off-peak period) and 3 cents/mile (peak period) depending on the time of day (Baker 2014).

There are opportunities in direct charging for achieving broad societal goals. DUC not only can recoup agency costs for construction and upkeep of the highway infrastructure; by internalizing costs associated with safety, travel delay, air quality, and other impacts, it can also attain effectiveness, efficiency, and equity in highway taxation. A well-designed DUC mechanism allows variable pricing—by location, time of day, and weight

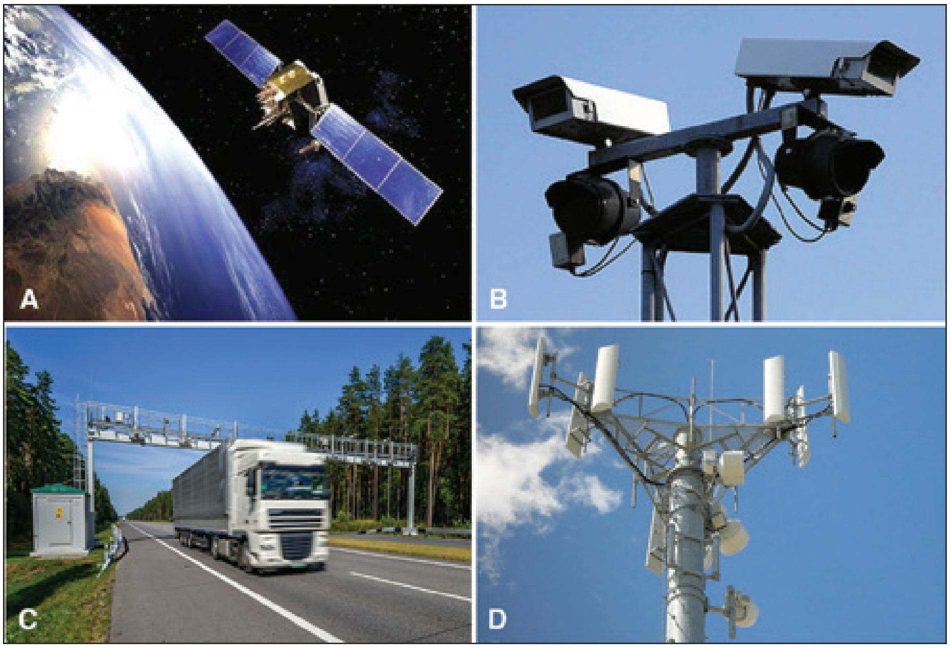


FIGURE 3 Technologies for Automated Collection of Direct User Charges. (A) Satellite Systems. Direct user charges based on mileage rely on GPS technology. Satellites provide location data. In-vehicle equipment receives the latitude and longitude data and uses it to measure travel. Source of image: US DOT Public Roads 69(5). (B) Automated license plate recognition. Reproduced with permission from Adrian Pingstone, Creative Commons. (C) Dedicated Short-Range Communications (DSRC). In-vehicle equipment is activated by DSRC as soon as the vehicle enters the monitoring area and deactivated when vehicle leaves the area. The technology operates in the electromagnetic spectrum's microwave or radio frequency range. Reproduced with permission from TrafficTechnologyToday.com. (D) Cellular Networks. Most roads are within the operating range of cellular networks, which thus represent a promising technology for direct user charging. Reproduced with permission from Telecomtalk, Creative Commons.

class—to ensure that the charges are appropriate and help generate a stable revenue stream. The scheme can be gradually phased in, starting with a flat fee structure by vehicle class only.

Technology for Implementation

DUC implementation would require deployment of appropriate technologies to monitor road use and to collect fees. To monitor use, an on-board unit (OBU) installed on the vehicle's windshield would communicate vehicle information to receivers on fixed locations (e.g., gantries) via dedicated short-range communication (DSRC) technology.[1] Alternatively, because smartphones are equipped with GPS positioning capability, they could be used instead of OBUs (Bomberg et al. 2009).

Direct user fees could be paid using in-vehicle or out-of-vehicle systems or a combination of the two. For each method, available technologies include electronic payment, optical vehicle recognition, and global positioning systems (GPS), and developments in the smartphone have unleashed a world of opportunities for tracking travel amounts and electronic payment through direct bank transfers.

Under the DUC scheme, road users would periodically receive (by mail, email, or text message) a bill for distance driven, with adjustments for time of day of the travel, location of road class travelled, and other aspects (e.g., operating weight). The user would verify the bill and pay using standard or pay-as-you-go methods (e.g., a smartphone or vehicle dashboard communication console). In certain systems, smart cards store credit that can be used for subsequent payments; these cards can be inserted and read by the OBU and removed as needed. Some technologies available for automated DUC collection are shown in figure 3.

Technologies for travel monitoring and user payment continue to evolve rapidly, and it is quite possible that when direct charging is finally implemented, the technologies used will be much more advanced than those of the current era.

Oregon's 2013 pilot study established some conditions that need to be fulfilled by DUC technology (Oregon DOT 2014):

- The DUC system must operate as specified.
- It should be reliable—that is, the mileage-reporting devices and account management system must not fail.
- It must be secure, to protect the software from potential cyberattacks.

[1] An OBU is a device with memory storage, computing capability, and an interface for communicating with DSRC, cellular networks, or GPS.

- It must be highly scalable and flexible enough to accommodate input from any vendor of mileage reporting hardware.
- The mileage reporting devices must not drain the vehicle battery or cause an increase in fuel consumption.

Overcoming Implementation Barriers

Implementation Costs

Direct user charging has fairly high startup costs for administration and operation, with an agency cost component and a user cost component. The agency costs include infrastructure and equipment capital costs, labor, future technological upgrades and maintenance, and administrative costs. The Oregon Department of Transportation estimated that implementation of its road user charging program would cost 10 percent of revenue raised ($4 million) for 100,000 users, and <5 percent of revenue raised (<$2 million) for 1,000,000 users (Oregon DOT 2014). These estimates were based on the technology available in 2013.

For the user, besides the fees for miles travelled, there are equipment costs. The Oregon DOT (2014) reported an estimated $50–$80 cost per user for the purchase of an external mileage reporting device, but with technological advances this cost is expected to fall significantly. Users may also incur indirect or intangible "costs" such as frustration and inconvenience during the initial period of implementation (Oh and Sinha 2010).

User Perceptions

To foster public acceptance of direct user charging, public outreach and communication initiatives must be pursued so that the public can fully comprehend and agree to the long-term user benefits of this highway revenue generation mechanism. Equity and privacy concerns must be addressed. Based on international experience (Sinha et al. 2011; NCHRP 2015), this can be done through balanced fee structures established from periodic cost allocation studies, exemptions, appropriate use of revenue generated by the DUC scheme, technology, and business rules.

Other Potential Challenges

The DUC mechanism should be financially efficient; that is, it must be capable of generating adequate revenues not only to replace the fuel tax structure but also to address the funding deficit, ensure revenue self-sufficiency, and pursue broad societal goals. It should be equitable: the user charges must be a good reflection of each user group's assessed "wear and tear" of the highway infrastructure as well as other impacts of road use. The program should be implementable in a way that ensures fairness to all users, in order to win public trust and acceptance.

Concluding Remarks

If properly implemented, direct charging will enable flexibility for agencies to pursue public policy objectives related to congestion, emissions, travel demand management, environmental protection, and equity associated with road use. For example, direct charging may cause traffic shifts to other routes, times of day, or modes depending on policy objectives.

Finally, an analysis of the financial sustainability of highway funding will not be complete without consideration of emerging trends in vehicle technologies. The trend toward driverless vehicles is evolutionary and incremental. Most vehicles already incorporate some advanced features that are part of this trend; over the next decade, it is likely that driving functions will become even more automated and that driverless operations on limited-access highways will be permitted for some vehicles with such automated functions. In fact, according to a USDOT report, fully automated driving (i.e., a driver is no longer needed to steer or adjust speed) could be commercially available within 20 years (USDOT 2014). The widespread use of this new technology will have impacts on both highway revenues and needs.

Direct charging is well suited for synchronous implementation with autonomous and connected vehicle technology. Future research will be necessary to identify the issues associated with the interfaces of these initiatives and to facilitate their deployment.

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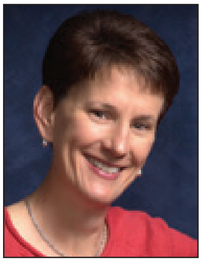
The coteaching model, complemented by assistive technology, allows students identified with learning disabilities to master STEM learning outcomes.

Leveraging Technology in the Coteaching Model for STEM Education

Kelly J. Grillo, Jane C. Bowser, and Tanya Moorehead Cooley

Kelly J. Grillo



Jane C. Bowser

Tanya Moorehead Cooley

Effective teaching is essential to guide student learning toward improved outcomes and ensure US innovation and economic development in science, technology, engineering, and mathematics (the STEM fields).

The increasing assimilation of students of diverse abilities in a single, "inclusive" classroom, together with enhanced accountability requirements in education (since the passage of the No Child Left Behind Act, for example), support the use of coteaching, an approach that pairs regular and special education teachers in the classroom to accommodate students' different learning abilities. And developments in technology make it an essential tool for engaging students with learning and other disabilities.

Kelly J. Grillo is adjunct professor of special education and technology, Lynn University, Ross College of Education. Jane C. Bowser is Technology Coordinator, High Point University, School of Education. Tanya Moorehead Cooley is assistant professor of special education, Eastern Connecticut State University.

This article draws on national data and recent research to illustrate the advantages of coteaching and other methods to successfully teach students of varying abilities in the inclusive classroom. Specific technical resources are briefly reviewed.

Background

According to an assessment by the Department of Education, learning outcomes for students in mathematics and science education in the United States are not improving (Aud et al. 2012). The scores of only about 30 percent of all US students are "proficient" or better on tests such as the National Assessment of Educational Progress (NAEP), Trends in International Mathematics and Science Study (TIMSS), and the Program for International Student Assessment (PISA). For the remaining 70 percent of students, radical changes to STEM education in the inclusive classroom are needed.

The Common Core State Standards and the Next Generation of Science and Mathematics Standards have increased rigor and significantly expanded demands on students to develop and use listening, reasoning, and writing skills. Students identified with learning disabilities (LD) require particular support in inclusive classes that focus on inputs (reading and listening) and outputs (writing and speaking) (figure 1) and on content mastery rather than on individual students' learning deficits.

To meet these requirements, teachers are exploring possibilities associated with the use of technology to preteach the basic skills needed, model laboratory procedures, and remediate skills as necessary. But technology alone is not enough if teaching professionals do not have the tools available to equalize the deficits of students with learning disabilities who may otherwise have an aptitude for and interest in STEM-related education and careers.

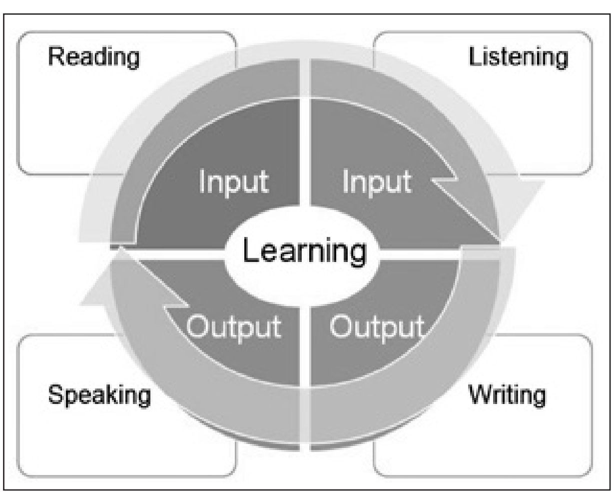


FIGURE 1 Inputs and outputs centered on learning.

Unfortunately, there is evidence that the manifesting characteristics of disabilities have been used to eliminate students from advanced STEM programs—for example, by using cutoff scores, reading levels, and other nominal measures that do not similarly limit other students in STEM education (Street et al. 2010). When provided the appropriate support tools for listening, reading, writing, and speaking, students identified with LD not only are competitive in STEM classrooms but may rank among the top performers.

This article describes tools and strategies that can be used in the classroom to help students identified with LD succeed in STEM courses, thereby encouraging them to pursue further education and careers in these fields. Educators can support all students in the general education setting with technology-embedded teaching practices, capitalizing on the combined strengths of two professional teachers who guide the learning process to improve outcomes in STEM.

Why Coteaching?

Greater diversity and accountability in education justify the use of coteaching in secondary education. The 2001 No Child Left Behind Act (NCLB) and the 2004 Individuals with Disabilities Education Act (IDEA) set the stage for incorporating larger numbers of students with special needs in the general education setting. With all children required to make learning gains under NCLB and new pressures associated with the Common Core standards in science and mathematics, there is more focus on the development of listening, reasoning, and writing skills.

Collaborative initiatives such as the coteaching model offer a way to complement content education with skills development for students who need extra support. Because the general education teacher is trained to deliver content and may have limited background or professional development in special education, coteaching with a special education teacher can address diverse learning needs in an inclusive classroom. The two educators have distinct, unique, and complementary roles to enhance achievement for all students (Dieker 2001).

In addition, use of the variety of widely available technology resources on the Web can make the coteaching model even more meaningful and useful than the traditional one-lead one-support model

(Scruggs et al. 2007). For example, a coteacher trained in both learning disabilities and technological resources can complement the regular teacher's lessons with demonstrations, either during or after class, of technical tools that facilitate comprehension. (Some of these tools are described below.)

STEM for Students with Learning Disabilities

The Case for Students Identified with LD in STEM

It is important to support students identified with LD in STEM subjects because their experiences in K–12 can shape the way they view their education and career goals. They may be inspired to achieve greater goals academically and professionally—or so discouraged that they avoid further education and risk missing out on careers in which they could have been successful.

According to a report to President Obama (PCAST 2012, p. 1), "the US graduates about 300,000 bachelor and associate degrees in STEM fields annually. Fewer than 40 percent of students who enter college intending to major in a STEM field complete a STEM degree." The report also states that "Economic projections point to a need for approximately 1 million more STEM professionals than the US will produce at the current rate over the next decade."

Students identified with LD are already rising to fill this gap. In 2011 the Access STEM Longitudinal Transition Study (ALTS) found that the number of undergraduates with disclosed disabilities[1] who receive a STEM degree had risen 67 percent since 2002 (compared to a 17 percent increase in non-LD STEM grads) (Burgstahler et al. 2011). At the graduate level these disparities are even more marked, with a 160 percent increase in STEM degree recipients with disclosed disabilities, while the number of those without such disabilities actually declined (−6 percent).

Bias Barriers in the Classroom and Workplace

Yet even as more students identified with LD choose STEM majors, they face barriers that other students may not encounter (Madaus 2006). A 2011 study reported that students identified with LD are perceived as "lazy, attempting to cheat or using learning disabilities to avoid schoolwork" (Lee 2011, p. 74). And a 2003 study of 245 faculty members at a land-grant university found that those in the college of engineering showed significantly less willingness to provide accommodation for students identified with LD than faculty in other colleges (cited in Lee 2011).

Real-world problem solving is routine for students identified with LD, who can model this skill for their peers.

Students identified with LDs are often dismissed as not able to learn in the most challenging curriculums, without regard for their abilities and strengths. The latter include real-world problem solving, which can be challenging for a teacher to skillfully model but is routine for students identified with LD who calculate reasonable solutions to everyday obstacles in order to meet even nominal daily demands. In the STEM classroom all students need to master problem-solving skills. There is thus an educational opportunity to invite students with disabilities to model the solutions to challenges they face, instead of using their challenges to divide them from their peers or exclude them from STEM programs.

Finally, parents of students identified with LD believe that employers in science and engineering fields may be even less willing to hire individuals with learning disabilities than those with physical disabilities. This may be because for many employers the term *disability* refers to a physical or sensory disability, not an "invisible" challenge such as a learning disability. Accommodations for those with learning disabilities are exceedingly rare in the workplace and not covered by the Americans with Disabilities Act (Lee 2011).

Coteaching with Technology: Rationale and Specific Tools

Rationale

American classrooms that assimilate students of varying abilities must capitalize on the tools that students favor (Dieker et al. 2011). Innovatively adapting the coteaching model and using technology that students are familiar with at a greater rate with a focus on learning

[1] A disclosed disability is an individual's diagnosed condition, governed under the Americans with Disabilities Act, reported with legal documentation to education service providers in order to receive accommodations or supports protected under the law to increase access to the curriculum.

TABLE 1 Ten tips for moving toward a "technology as coteacher" model

Request tech-enabled volunteers to work on PLC/team in STEM content areas.	☐
Determine the local needs for students to support improved STEM outcomes.	☐
Layer supports that are known to be needed (e.g., to develop organizational, writing, language, social skills).	☐
Add technology supports to classes that have the highest D–F rates (typically Algebra I and biology).	☐
Ask teachers who have high D–F rates to allow the tech-enabled PLC/team to set up technology remedial centers in their classrooms for extra support.	☐
On professional development days have technology coteachers demonstrate support stations for STEM-focused educators who teach students identified with LD (focus on content supports).	☐
Monthly: Encourage members of the technology PLC to share success stories/data from students who are increasing their achievement in STEM classes.	☐
Quarterly: Highlight student testimonials of learning and how their engagement/excitement/grades increased with the use of technology-enabled strategies in their STEM classes.	☐
Create STEM technology buddies for peer mentoring with tech support tools, to help students gain fluency in the use of assistive/learning technology tools to increase fluency in STEM subjects.	☐
Create a teacher-teacher mentoring program to generalize the use of technology across all STEM curriculum areas.	☐

PLC = professional learning community; STEM = science, technology, engineering, mathematics

outcomes may increase the participation of students identified with LD (and other disabilities) in STEM-focused classrooms. Table 1 offers steps to help teachers move toward using technology in a coteaching model.

The ability to provide students with assistance however, wherever, and whenever they need it makes technology an ideal "coteacher." It can be used by students both in the classroom and at home, enabling them to experience the same interactions with content as their peers.

The technology tools shown in table 2 and briefly described below are easy to use and do not require much training or technical expertise for either the student or teacher. We include tools for learning as well as other disabilities (e.g., vision and hearing impairment) that affect students' ability to access and grasp classroom content.

Specific Tools

Inputs: Reading, Listening

Reading supports are now readily accessible to Windows and Mac users. VoiceOver supports visual impairments by reading all text and commands to the student, with adjustments and enhancements such as Speak Hints, Speaking Rate, Phonetics, Pitch Change, and Compact Voice. In addition, output can be provided to a Braille device. Other vision supports make it possible to zoom, enlarge text, and increase contrast.

A Windows-compatible option is the NonVisual Desktop Access (NVDA) screen reader, which can be downloaded to a USB drive and used with any Windows computer, making it convenient for students who do not have an iPad or laptop that can be taken with them to school.

The affordability of the iPad and the many apps designed to assist learners of all types make it a go-to device for listening supports. For the hearing-impaired, mono audio hearing supports can be activated for either the left or right ear.

The Notes Plus app enables students to take notes using handwriting or typing, but one of its main benefits is the microphone, which can be used to record notes, class lectures, and other information that the student can play back any time to review content as needed. In addition, the app's easy-to-navigate design helps students with organizing their ideas for class.

A convenient and easy tool for teachers is Voice Thread, which allows them to upload and record content that can be conveyed to students via email or posted on a webpage or blog. Being able to listen to content as needed not only reinforces the material but also enables students who have difficulty focusing in class to hear the spoken content in an alternative environment. Voice Thread also has a mobile app that runs on an iPad, iPhone, or iPod Touch.

Outputs: Writing, Speaking

Cast Science Writer is a free Web-based instructional tool developed to support middle and high school

TABLE 2 Technology-coteacher options

Mode		Tool	Website	Cost
Inputs	Reading	NVDA	www.nvdaproject.ord	Free
		Accessibility for Mac and iPad	www.apple.com	Free
	Listening	Notes Plus app	http://notesplusapp.com	$7.99
		Voice Thread	www.voicethread.com	Free
Outputs	Writing	Cast Science Writer	http://sciencewriter.cast.org	Free
		Dictation	www.apple.com	Free
	Speaking	Voki	www.voki.com	Free (expanded version with more features and customizations $29.95/yr)
		GoAnimate	www.goanimate.com	Free (expanded version with more features and customizations $99.00/yr)

students in writing science reports. It is a feature-rich program that is based on the principles of Universal Design for Learning (UDL). It includes built-in report structures that provide assistance in the writing process, checklists for editing and revising science reports, and a journal for taking notes, organizing thoughts, and posing questions for later review. Animated assistance supports student learning with helpful hints, grammar considerations, and examples. A Speechstream toolbar, designed by Texthelp with a dictionary and translator, enables students to have text read back to them at any time. This feature helps students with proofreading and finalizing their reports.

For students who need help with writing and/or typing, the Voice Dictation feature of the 3rd generation iPad is available as a keyboard button. Spoken words and punctuation are transcribed as text with appropriate punctuation; for example, if a student says “the car was moving 20 miles per hour period,” Dictation writes “The car was moving 20 miles per hour.”

Two sources for speaking supports are Voki and Go Animate. With Voki Classroom, teachers can manage student accounts in a secure environment and recording time is extended from 60 to 90 seconds. Students can personalize the Voki site by creating an avatar and choosing the background as well as various enhancements that invite them to use their creativity to personalize this resource. The avatar can then be linked to or embedded in blogs, wikis, and even SMART Notebook files (with Notebook 11). Input for the avatar to speak can be entered by keyboard, microphone, or telephone. With Voki’s speaking tool students can explain their understanding or demonstrate their learning in a fun and creative way.

GoAnimate can provide student support in both content understanding and communication. With a free individual GoAnimate account or an inexpensive GoAnimate4Schools account, stories involving two avatars can be developed, enabling dialogue to enhance learning and communication. Lengthy and customizable videos can be created, but in most cases short clips made with point-and-click features are sufficient. Like Voki, input can be provided by typing text or recording from a microphone. GoAnimate movies can be linked to or embedded in various websites and blog utilities including Google Sites and Blogger.

Conclusion

The programs and apps described above are just a sampling of those available among the technological options for coteachers and students. They can provide individualized support, tailored to each student’s abilities, in inclusive STEM education and are easy to learn and use, cost-effective, and generally intuitive.

Technology can increase students’ proficiency with 21st century tools, but it is up to teachers to shape learning opportunities that improve STEM learning outcomes. The modern STEM classroom should arguably be a place where students communicate and collaborate, there is positive student-teacher discourse, students pose questions and test them via research on plausible hypotheses using technology-assisted tools, and newly developed knowledge is communicated through technology-enabled outlets (e.g., blogs and electronic publishing methods).

It is important not to use the label of “disability” to further marginalize students or limit their educational opportunities. Rather, teachers should use available and ability-appropriate tools to help students learn.

To ensure that all students have the opportunity to pursue STEM majors and occupations, classrooms can support the achievement of learning targets through the coteaching model, in which two professional coteachers use technology to allow and encourage students to explore learning in a more personal, effective, and engaging way.

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DC power, largely abandoned by 1890, is now making a remarkable comeback in generation, distribution, storage, and use.

Electric Power and DC's Renaissance

Lionel O. Barthold

Dennis A. Woodford

Lionel O. Barthold and
Dennis A. Woodford

In 1882, 82 customers with 400 of Thomas Edison's new electric lamps signed on to America's first central electrical supply system. Direct current (DC), at 110 volts, fed those loads through copper cables that emanated from dynamos at Edison's Pearl Street generating station in Manhattan (figure 1). Edison, quite aware of Ohm's law, must have lost sleep worrying about how he could keep up with the soaring demand for current using copper wires at such a low voltage.

Meanwhile George Westinghouse, also aware of Ohm's law, accepted the help of Nikola Tesla—an advocate of alternating current (AC) who, in frustration, had abandoned Edison—in adapting a new device called a *transformer*. It was modified to convert the output voltage of AC generators to a higher voltage, distribute it at that higher voltage, then step it down again to 110 volts for consumption. For the same level of power, higher distribution voltage requires less current and therefore smaller wires. That general system architecture flourished and prevails to this day.

As demand for electricity grew exponentially, transformers allowed distribution networks to be overlaid with successive layers of higher and higher

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Lionel O. Barthold (NAE), a power transmission consultant, is a Life Fellow of IEEE and retired founder and CEO of Power Technologies, Inc. Dennis A. Woodford is former executive director of the Manitoba HVDC Research Centre and now president of Electranix Corporation of Winnipeg.

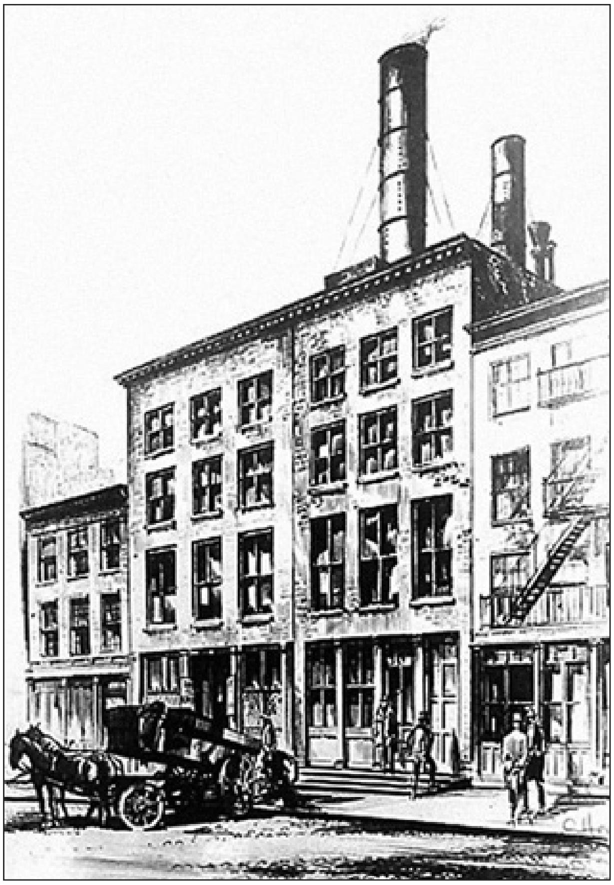

FIGURE 1 Thomas Edison's Pearl Street Generating Station, New York, 1882. Image credit: Consolidated Edison of New York.

voltage until America's highest voltage lines, rated for 500 or 765 kilovolts (kV), now span several states and carry thousands of megawatts (MW); power is then progressively stepped down through those networks for delivery to their 110 or 220 voltage loads. At each voltage level, systems were made sufficiently redundant to lose one or two major lines without any interruption of power to users.

Early Power Generation/Supply Structure

Coal-burning power plants, a dominant source of early power generation, grew in rating to individual generators of up to 1,000 MW. The plants were built close to coal and cooling water resources and sent their output to load areas via high-voltage AC transmission lines on rights of way, which, with the help of eminent domain laws, took the shortest route to electrical loads and to one another. The breadth of interconnections grew to the point that generators in one area could back up those in another when one had to be shut down.

Power was supplied by vertically integrated, interconnected regional power companies. That pattern of growth ended in the 1960s when

- concern for the environment ended an era of easy transmission line permitting;
- standard AC transmission voltage levels ended their long progression of increases;
- economies of scale in generator size reversed as gas turbines made big inroads into the generation mix;
- nuclear accidents dimmed the bright promise of nuclear energy;
- industry structure went from vertical to horizontal and from regional monopolies to regulated competition; and
- transmission grid management became very sophisticated and software-dependent; "smart grids" progressed from concept to necessity.

In speculating where things may go from here, it will be instructive to track the alleged demise of DC and its subsequent resurgence in the power generation, storage, delivery, and consumption matrix.

Resurgence of Demand for DC Power

Demand for DC, overwhelmed by AC at the turn of the 20th century, did not exactly die. Though AC dominated early electricity usage, elevator systems and subways still needed variable-speed motors, which DC alone could then support. Hence DC stayed on as a footnote to the electricity supply menu in New York City until as late as 2007 and is still available from other metropolitan energy suppliers (Fairley 2012). Furthermore, with each passing decade new DC-only loads emerged, primarily in industry (e.g., for aluminum reduction, electrolysis, and metal finishing). That demand was usually met by AC power purchased from the grid and converted back to DC by the user.

But DC's resurgence in demand was inadvertently started by Edison himself! While tinkering with incandescent light bulbs in 1883, he noticed that he could get DC current to flow *through a vacuum* from a hot filament to a plate, but not in the reverse direction. In 1904 Sir John Ambrose Fleming, a British scientist, used that idea to patent a glass-enclosed "diode," a one-way valve for electricity. A decade later Lee de Forest put a metallic "grid" between the filament and the plate and, with a very small amount of current, controlled a much larger DC current flow through the tube, thus introducing the "triode" and with it the ability to progressively strengthen and control a very weak signal. That launched the electronic age, first with vacuum tube–based transmitters and radios, then with solid state valves whose expanded usefulness gave birth to a revolution in communications, computation, and control that has literally changed civilization. *Every* such device first needed conversion of AC to DC for its operation.

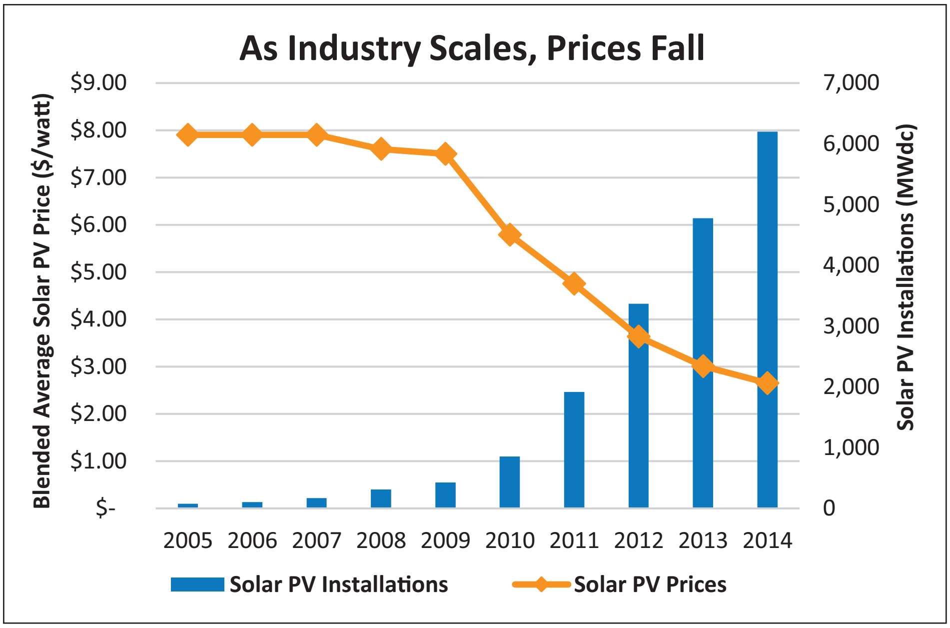

FIGURE 2 Market growth and cost reductions in solar voltaic generation. PV = photovoltaic. Reprinted with permission from GTM Research and the Solar Energy Industries Association.

Meanwhile the incandescent light bulb, which spawned the centralized electric supply industry, gave some ground to fluorescent and neon lighting (both AC-dependent) for a few decades. Then electroluminescence—the tendency of certain crystals to emit light of their own characteristic color when subject to small DC currents—became the focus of research the world over and eventually led to light-emitting diodes (LEDs), which now enable visual interface with watches, smartphones, television screens, and advertising signs, and most recently have become the basis for area lighting. LEDs operate on DC from batteries in handheld devices, but from AC-to-DC converters in computers, TV sets, and even individual LED lamp bulbs.

In a modern household, air conditioners, fans, and portable power tools need variable-speed motors, a feature that DC motors can best manage. Where such motors are used, AC is converted to DC within each appliance. Other household loads such as resistive heating can inherently operate with either DC or AC.

Thus the majority of both household and commercial electric consumption may soon be DC, not AC. The advent of electric or hybrid automobiles and their DC charging load will tip the balance to DC's favor in many households.

DC's Emergence as a Form of Power Generation

Coal, gas-fired, and nuclear power plants still dominate electric energy production in developed countries, and are not easily adapted to produce DC. But new generation *additions* are another matter. In 2015 more than 65 percent of America's new generating capacity came from solar power and wind (Alhart 2015)!

Solar

Solar's share of world electrical generation, inherently DC, is growing by about 55 percent per year (about 40 percent per year in the United States), compared to worldwide growth in electricity demand of just 3 percent per year (SEIA 2013). While America's solar growth has been driven in part by subsidies, today's cost per watt is one-third of the cost 10 years ago (figure 2), and approaches parity with grid-delivered power in some regions. Furthermore, as rooftops demonstrate, solar generation can be local. As the effects of global warming are increasingly felt and energy storage becomes a more effective "levelizer" of irregular solar and wind energy production, solar's rate of market penetration will likely continue at a very high rate.

Wind

Growth in wind generation too is dramatically outpacing overall electricity supply growth, expanding by roughly 20 percent per year over the past 15 years—six times the rate of worldwide electricity consumption (GWEC 2015). In Europe, where population density puts high pressure on air quality, roughly 30 percent

FIGURE 3 Early concept of Atlantic Wind Connection for Virginia, Maryland, Delaware, and New Jersey. Red = phase 1: New Jersey link. Blue = phase 2: Delmarva energy link (Delaware, Maryland, Virginia). Grey = phase 3: Bay link between the phase 1 and 2 connections. Reprinted with permission from Atlantic Grid Development, LLC, available at AtlanticWindConnection.com.

of all new generation addition since 2000 has been through wind technologies (EWEA 2015).

Wind turbines generate AC, but offshore wind farms, taking advantage of steadier winds and lower aesthetic impact, usually do so at a frequency dependent on wind speed. There being no easy way to convert variable-frequency AC to standard-frequency AC, AC current must first be converted to DC and then back to standard-frequency AC. Thus at its initial first step, this form of wind generation too can be considered a DC source, leading to the question: With recently developed DC-to-DC transformers, why not take the "intermediate" DC voltage and transform it to a higher DC voltage for collection, then to a still higher DC voltage for cable transmission to shore (Barthold et al. 2015)? That approach simplifies electrical architecture, takes advantage of lower-cost DC cable, and allows that cable to supply reactive power to the shore system rather than consume it. One such offshore wind development, with the potential to link East Coast states from New Jersey to Virginia with up to 6,000 MW, is being proposed by the Atlantic Grid Development, LLC (figure 3; Taiarol et al. 2014).

Energy Storage, Too, Is Going DC

Ever since the classical (AC) system model gained sway, the incentive for *storing* electrical energy during periods of low demand and retrieving it during periods of high demand was apparent. Doing so eliminated the need for extra generators just for peaks in demand. As early as the 1890s, Swiss engineers arranged to pump water into a high reservoir at night, then discharge it through hydroelectric turbines to a low reservoir *producing* electricity during daylight hours. "Pumped hydro" remains the dominant and lowest-cost source of large bulk energy storage.

But DC-directed shifts in electrical generation and use are changing the storage game dramatically, in many cases shifting it to individual homes or businesses. Output of both solar and wind generators, being highly variable on an hour-to-hour basis, add a new point-of-use incentive for electricity storage, one benefitting both the homeowner and the electricity supplier but demanding downward scalable technology (Gilpin 2015).

While flywheels, compressed air, "supercapacitors," and other downward scalable means share a small niche in that localized market, the big winner appears to be advanced lithium-ion (li-ion) batteries, the cost of which has dropped by about 65 percent in just five years. Their applications, forecast to increase at roughly 45 percent per year (IRENA 2015), now include home-size storage systems at prices approaching those of gas-powered generators. With that option homes and businesses will remain connected to the grid to purchase (and sell) electricity, but remain independent for critical loads if the grid fails. Electric vehicles, inherently DC, will boost domestic DC demand and be a source of domestic energy storage (Tweed 2015).

Battery storage is making inroads at the power *system* level as well. At the Imperial Irrigation District in Southern California, 2016 is the target operational date of a 30 MW li-ion unit.

Considering the prospect of eventual DC dominance in home energy use and the potential for both generation and storage of electricity at the consumer level, it's entirely possible that the wires linking homes to the grid may one day include a DC supply along with, or perhaps eventually supplanting, AC . . . which would, at a massively larger scale and through a dramatically more sophisticated delivery system, take the industry back to where it came from.

DC's Growth in Energy Delivery

As with energy supply, consumption, and storage, the same shift (albeit more slowly) from AC to DC can be seen in large-scale regional exchange of electric power. AC's early dominance in power transmission, driven by the availability of transformers to boost voltage, was first challenged in the 1930s when engineers at General Electric's Schenectady plant asked the following: Why not (1) step low-voltage AC up to high-voltage AC with a transformer, (2) convert the high-voltage AC to high-voltage DC for transmission to another location, (3) convert the high-voltage DC back to high-voltage AC at that location, and, finally, (4) step high-voltage AC back down to use-level voltage at the receiving end of the line?

To demonstrate the idea, General Electric built a 15 kV, 23-mile DC transmission line to bring 150 kW of DC power from a hydroelectric plant in Mechanicville, New York, to Schenectady. Conversion of electricity from AC to DC and back again was achieved with a complex array ("bridge") of electrical "valves," each able to conduct electricity in one direction only and which, by being "fired" in the right sequence, can either convert an AC voltage, which varies in both polarity and magnitude, to a constant and unvarying DC voltage or do just the opposite. Those valves were then composed of evacuated tubes containing mercury. It worked!

That prompted Swedish engineers to build the first commercial DC project in 1954: a 98-kilometer undersea cable link to supply 20 MW, at a voltage of 100 kV, from the Swedish mainland to the island of Gotland. That succeeded and was followed by a number of other projects, some using overhead DC transmission lines and inspiring a large US DC project, commissioned in 1970, that eventually sent over 3,000 MW of inexpensive hydroelectric power from the Pacific Northwest to Los Angeles at 500 kV DC.

> *Offshore wind farms require conversion of variable-frequency AC to DC and thus can be considered a DC source.*

Why go to the trouble of converting AC to DC at one end of a line, then back to AC at the other?

1. DC is a more efficient way to transmit power. Because AC voltage varies in magnitude its effectiveness is roughly 30 percent less than a constant (DC) voltage.
2. Power flow on an AC line cannot be directly controlled, for somewhat the same reason the tension on one of many load-bearing strings of a hammock cannot. In both cases individual line loads are determined by the system in which they serve. Thus large wires on an AC line can't always be used to full advantage. DC power *can* be controlled, with the full current-carrying capability of wires used constantly.
3. AC power lines have a characteristic (an electrical cousin of elasticity) that limits the practical distance power can be transmitted at a given voltage. There is no such limit, other than tolerance for losses, to the distance that DC can transmit power.
4. Underground or underwater cables constantly need a certain amount of current per mile for "charging." Charging power is called *reactive power* in the trade. If a cable is very long the charging current itself will use all the cable's current rating. DC cables need no charging current.
5. DC interconnections can help prevent the electrical breakup of systems that have only AC ties.

As these advantages were increasingly recognized, the number of high-voltage DC transmission applications grew steadily wherever transmission distance exceeded

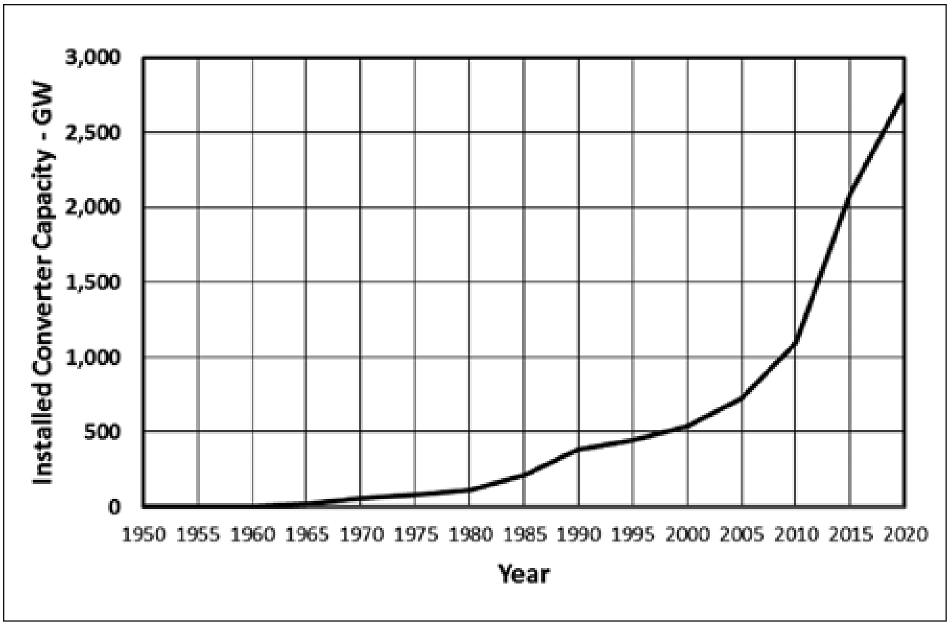

FIGURE 4 Growth in worldwide DC transmission capacity, 1950–2020. GW = gigawatts.

a "break-even" distance—the distance at which DC's savings in transmission line cost plus the value of its operating advantage became greater than the cost of converting AC to DC at one end of a line and back to AC at the other.

The Emergence of Supergrids

By 2015 over 2,000 gigawatts of DC projects were in operation throughout the world. DC's growth in gigawatts of conversion capacity (figure 4) promises to accelerate as system planners the world over foresee DC "supergrids" overlaying and potentially interconnecting AC systems in all of the world's major electric power generation and consumption areas—a development that could more than double the number of existing DC installations (Gellings 2015). Supergrids can

- limit the need for new generation additions by "pooling" generating capacity over a very wide region, each with peak demands offset in time;
- allow heavier loading of local AC networks without risk of blackouts; and
- equalize irregular patterns of wind and solar generation to make such "green" resources more widely available.

Figure 5 shows what's foreseen as a possible North American DC supergrid.

Supergrid Plans and Designs

Early in the evolution of the supergrid concept, planners recognized that its realization would require an economic DC-to-DC transformer to (1) allow the grid's connection to or integration of existing DC lines of differing voltages and technologies and (2) control flow on long DC lines, formerly individual projects but now in a networked configuration. Foreseeing that need, Friends of the Supergrid, one of many European planning groups, recognized in 2014 that DC-to-DC transformation was an essential element in supergrids (FOSG 2014), in response to which a number of DC-to-DC transformer designs have been proposed—all based on capacitive energy transfer rather than the magnetic transfer characterizing AC transformers. One proposed solution, capable of very high ratings and very low losses behaves, in a DC system, exactly as a magnetically based transformer does in an AC system (Barthold et al. 2015). That innovation is expected to further accelerate DC's inroads into the power transmission market.

Technical Advances

The dramatic growth of DC transmission has been fueled in substantial part by advances in AC/DC conversion technology that have kept costs relatively stable while increasing DC's value to the host AC system. Mercury arc valves, for example, gave way to water-cooled solid state (Thyristor) valves in the 1970s and then, in 1997, to integrated gate bidirectional transistors (IGBTs), which allowed a bridge architecture (the voltage source converter, VSC) that changed the game significantly. Until then AC/DC converter stations needed to be fed "reactive" power from the AC network just as AC cables need to draw charging power from such networks. VSCs allowed terminals to *supply* reactive power to the AC system rather than drawing it from that system. Research into rectifying materials other than silicon, the basis for IGBTs, may lead to

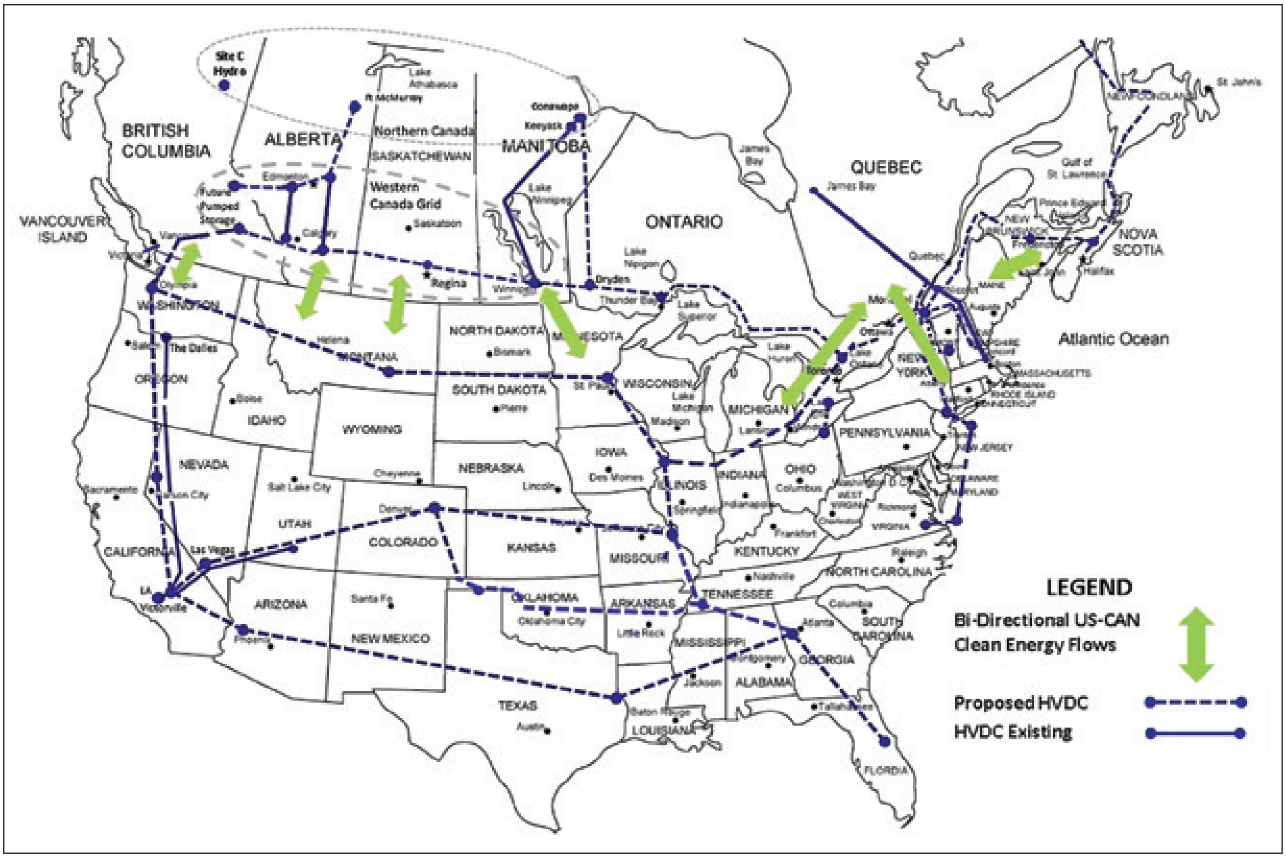

FIGURE 5 Prospect of a North American direct current (DC) supergrid overlaying and interconnecting major electricity consumption and supply regions. HVDC = high-voltage, direct current. Image by Dennis Woodford (Electranix Corporation) and Ward Kemerer (Hydro Battery Inc.), based on US supergrid concepts provided by the Midcontinent Independent System Operator (MISO).

bridges capable of substantially higher current ratings and lower cost per megawatt of capacity.

Microgrids and Other Changes in Power System Architecture

Changes in technology notwithstanding, the evolution described above would maintain the classical hierarchical electricity delivery system structure. A DC grid would allow generation in California to benefit users in the Midwest and failures in the Midwest to be rescued by East Coast grids. This hierarchical architecture, together with growing sophistication in the control of power systems and competition among power suppliers (within constraints of the transmission network), has minimized electricity costs to consumers.

Yet while a hierarchical system implies *interdependence*, there's a growing countertrend toward a degree of local *independence*. Microgrids started simply as a convenient way of distributing AC and (through conversion) DC power in a factory or commercial building. But the advent of local energy storage and site-based generation is bringing with it a trend to expand microgrids both functionally and geographically to form a partially autonomous source of power after full or partial loss of supply from the primary grid (Backhaus et al. 2015). Interest in a degree of local independence is fueled in part by concern over the vulnerability of the very large, highly sophisticated, and computer-dependent "smart" interconnected system to cyberterrorism.

Microgrids connected to the primary grid could buy and sell electricity through the primary grid, the latter acting as an energy marketplace. A supergrid would make that market continentwide and accessible even to the homeowner.

Microgrids, regardless of purpose, also support a shift away from AC-to-DC conversion *within individual devices* in favor of single-point, more efficient conversion to a common DC supply source. They will encourage an end to double conversion of rooftop DC generation (i.e., DC to AC for household supply, then back to DC for loads that demand DC), a transformation now achieved by individual AC-to-DC converters. Microgrids may encourage delivery of DC as well as AC or ultimately *instead of* AC directly to homes and businesses.

Where from Here?

AC power has served both suppliers and users of electricity extremely well, having the inherent advantages of simplicity and, to a large degree, self-regulation. In elementary terms, when a new electrical load is switched on in an AC system, incremental power flows to that load without instruction or control. Simultaneously, elsewhere on the same system, a governor responds to increase its power output by the same increment . . . not by a signal sent from the new load but from what that generator sees in system behavior at its location on the system. What could be simpler?

In contrast, a DC transmission line needs to be told, through its converter terminals, how much power to send at one end and how much to receive at the other. However, as in many facets of modern industry, the advantage of simplicity is increasingly threatened by today's explosive growth in sophistication of control and communication. Thus AC systems may one day be rendered vulnerable to the continuing advances in DC technology. Further fueling that prospect is the fact that AC equipment and transmission technologies are very mature, while those supporting DC forms of generation, conversion, and use are still evolving rapidly.

Edison would smile.

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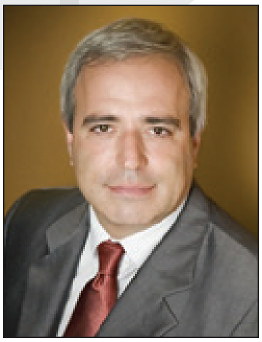
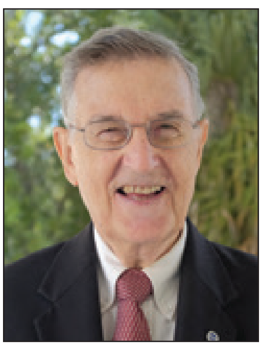
Op-ed

The Symbiosis of Science and Technological Innovation



Jonathan D. Linton is Power Corporation Professor in the Management of Technological Enterprises, University of Ottawa, and academic head, Laboratory for Science and Technology Studies, National Research University Higher School of Economics in Moscow.



Daniel Berg (NAE) is Distinguished Research Professor, University of Miami School of Engineering.

The symbiosis of science and technology plays an integral role in innovation. Science is needed for innovation regardless of whether science or technology leads. We propose mission-oriented research and fortuitous observation as the dominant trajectories for discovery that are not based on fundamental science.

In addition to existing programs and policies that focus on the conversion of science to innovation, programs and policies that encourage the development of science from innovation should be developed. For example, the technology-to-science link can be made stronger in education by encouraging the exploration of results that violate expectations when teaching the scientific method to students.

Although the importance of science in the creation of social and economic benefits is well articulated, recognition of the critical importance of science for inventions driven by technological advance is limited. Examples such as the large economic gains from 19th century technological advances in an America with limited science capabilities seem to suggest that science may be unnecessary for economic growth.

But science is needed whether it leads or follows technological advances.

Advances such as thermodynamics, photography, incandescent lighting, transistors, and photocopying are all cases in which technology led science. A specific mission—light from electricity, a reliable replacement switch for vacuum tubes, and an inexpensive way to copy documents—led to a technological advance before science could. Alternatively, thermodynamics, penicillin, and photography are the results of observation, capture, and refinement of an unanticipated event.

Regardless of the path to technological advance—whether mission oriented or serendipitous—the search for understanding (science) needs to follow. Without scientific research the new technologies mentioned above would have been impossible to control, manage, refine, and fully exploit. In fact, a substantial part of industry basic research is the pursuit of understanding of useful observed phenomena. For example, Xerox's quest to understand the science behind photocopying not only greatly improved the quality of black-and-white copying but also resulted in the development of color photocopying.

Science replaces faith in technology with fundamental understanding. Without science, technical discovery would be seen as either mystical or a wonderful "black box." Scientific research into technological discovery offers deeper understanding of each technological advance and of the world around us.

Recognizing this link can inform better policies and approaches to encourage industrial research. The following illustrate approaches to create opportunities.

For many years, fears of industrial collusion and threats to academic freedom created a barrier between firm-firm and firm-university interaction. Changes to antitrust regulation allowed for precompetitive basic and applied research partnerships such as Sematech (the semiconductor industry) and the Industry Cooperative for Ozone Layer Protection (ICOLP). The trend toward entrepreneurial universities is encouraging various types of transfers of applied and basic scientific knowledge. The NSF Research Centers catalyze the development of firm-university interactions, as the research centers require matching grants and advisory boards involving industry. Programs operated by MITACS and the Natural Sciences and Engineering Research Council (NSERC) in Canada provide funding for graduate students to solve industry problems of a technical nature that are related to the student's field of study.

The encouragement of interactions leading to a virtuous cycle of investigation between science and technology is also impacted by industry structure. Bell Labs had tremendous success in both the basic and applied sciences, in part because (1) research was collocated with production, ensuring manufacturability and scalability, and (2) senior management was responsible for both basic science and applied technology, so potential links between advances were more apparent.

In terms of the government role, policy and regulation need to catalyze interactions between stakeholders. There is a need to avoid well-meaning policy that creates unanticipated consequences that block the flow of knowledge between science, technology, invention, and innovation. The patent system has been described as such a policy, because patent trolls use the system to create financial barriers to inventors by registering ideas that the trolls do not intend to commercialize.

Perhaps more significant is the need to enhance how the scientific method is taught. Master's and doctoral programs greatly emphasize the scientific method, which is critical for research, but they need to put greater stress on searching for, observing, and exploring unexpected results. Exploration of the unexpected makes it possible to identify paradigm-breaking phenomena with useful technological implications. A focus on the presence of the unexpected can increase advances in both science and technology.

In summary, recognition that the pathway to innovation can be a function of either science leading to technology or technology leading to science is helpful in terms of communication with the public, policy, and effective education and practice.

An Interview with . . .

Sandra Magnus

Sandra H. Magnus, engineer and former astronaut, is executive director, American Institute of Aeronautics and Astronautics (AIAA).

RON LATANISION (RML): Sandy, we're very happy to have this opportunity to talk with you. I understand you studied electrical engineering and physics at the Missouri University of Science & Technology, and then got your PhD in materials science and engineering from Georgia Tech. From there you went to McDonnell Douglas and then to NASA. How did that all occur?

SANDRA MAGNUS: Well, I'll briefly give you my life story because that's really what it's all about. I was about middle school age when I decided I wanted to be an astronaut. That was my dream. But I didn't know engineering existed, so now when I talk to people about engineering I make the point that we have to expose young people to engineering as early as possible so they know it's actually a career choice for them. You can't choose something you don't know exists!

I focused on physics. Throughout middle school and especially high school I had access to the sciences—biology, chemistry, and physics—and physics resonated with me the most. I planned to get my PhD in physics and then apply to NASA.

I got to college and that's where I discovered engineering: 'Oh, this is cool.' I love physics, and I wouldn't have done it any other way because you can go anywhere with physics, but when I discovered engineering I realized you can take physics and do something with it.

Around that time I also got a little tired of being in school and wanted to see how this all worked in the real world, so I decided to get a job instead of going straight to grad school full time. I always liked electromagnets and that side of physics, as opposed to the mechanical side—I'm more of an electromagnetic quantum mechanics kind of girl as opposed to a structures kind of girl.

I got a job at McDonnell Douglas and got involved in stealth technology. That was really cool. I started doing my electrical engineering master's at night school, because I knew I wanted to get a PhD someday and electrical engineering became interesting to me while I was in college. I had taken an electrical engineering class every semester just for fun while I was in college to learn more about it—I'm a typical nerdy engineer scientist, I totally own it.

At McDonnell Douglas I was exposed to what it takes to build an airplane—we were designing an airplane from scratch—and that got me interested in materials. So much of what we were doing—or what we could or could not do, actually—was intriguing from the viewpoint of materials. I didn't know anything about the field of materials science before McDonnell Douglas. I liked it because it was a blend of science and engineering, physics and chemistry.

After about three years I started thinking, 'oh, this would be fun to get my PhD in,' so I got my PhD in materials science at Georgia Tech. Then I decided I had a pretty decent-looking resume—I'd completed my PhD, which was a goal, and I had some work experience—so I applied to NASA's astronaut program. I was accepted and spent 16 years at NASA doing space stuff. Then I had to grow up and get a real job, which is what I do now.

But back in 1978 I was a freshman in high school and that's the year they took the first women astronauts. I remember very clearly reading the front page of the newspaper with the announcement that women were accepted into the astronaut program and I thought, 'wow, there's a path.'

But I didn't know what the path was. I knew I wanted to do it and I knew I wanted to study physics, but at that age I was still kind of clueless. I was going to go get a PhD and apply to NASA. That was as far as I had gotten.

CAMERON FLETCHER (CHF): How did you find out what the path was?

MAGNUS: I called down to the Johnson Space Center to find out—this was before the Internet—I called and said, "Can I talk to somebody about being an astronaut?" There's an astronaut selection office and they send you information. And when I wanted to get an application (this was before USAJobs.com) I called the Johnson Space Center and said, "I want to get an astronaut application," and they transferred me to the astronaut selection office, which sent me an application, and I filled it out and sent it back. It's not hard to get the information. You just have to look for it.

CHF: That's such a delightfully low-tech approach.

MAGNUS: We didn't have the Internet then. Now you look up on the Internet, 'this is what it takes to be an astronaut' and find out the minimum requirements: you have to have a bachelor's degree in a technical or science or engineering field with three years of experience, or a master's with two years of experience, or a PhD with zero years of experience, or you can have a medical degree. All the requirements are posted.

Magnus on the last Space Shuttle flight, the Atlantis (STS-135), July 2011.

RML: I was wondering about that. Obviously, science or technology experience is valuable, maybe essential. But what about when you're on the International Space Station, for example—it's quite a different social dynamic than when you're in an office or a classroom. Are social skills highly evaluated in people who are candidates for the astronaut corps?

MAGNUS: This is what I tell students. NASA gets 7,000 or 8,000 applications every time they have a selection. To be competitive you need a master's degree. You don't need a PhD, although it certainly doesn't hurt. They take a mix of master's and PhDs.

The other thing they are basically looking for is well-rounded people—people who can communicate, work on teams, and learn. One of the things you have to be able to do as an astronaut is learn—you are always learning. And if you can work on teams and have good people skills, that's all part of being a well-rounded human.

As far as living on station, you've trained with these people for years, you know each other—it's like having another family. If you have siblings, think about the dynamic. You grew up with your siblings, you know each other really well—you know when they're unhappy, when they're frustrated, you know what makes them happy…. It's really a matter of picking the right crews to fly together to get the right dynamics and mix of skills needed.

RML: I taught at MIT for almost 30 years, and in the materials science department some of my faculty colleagues were involved in experimentation in space—for example, in semiconductor crystal growth—so astronauts would come periodically to meet with them and talk about the relevant experiments being planned in space. I was always impressed that the astronauts I met not only were very technically capable but also had compelling personalities. I think a cross section of people in general would be unlike the cross section of astronauts that I met. One of them was Jack Schmidt, who went on to become a senator from New Mexico. So I'm wondering about the social skills and whether there is some sort of prerequisite characterization of the corps that focuses on aspects like that.

MAGNUS: I think it goes back to the fact that they're looking for well-rounded people who can function in teams. An attractive applicant for the astronaut corps is not somebody who sat in a lab all the time. It's someone who is open to new experiences and has a broad variety of experiences. And it doesn't have to be just work experience, it can be hobbies too. They want people who have a well-founded desire for learning, a curiosity about things, and who can be articulate. But there's no formal definition of must-have social skills.

It's like any job interview: they're looking to see if the candidate fits into the culture. For the NASA astronaut interview, there are about 15 people on the selection board (I don't remember the exact number). You go into this room and they've got a stack of paper on you 2" thick because they've done a lot of research just to see if they want to interview you. You sit down at the table and they basically say, "Start at high school and tell us about yourself." Of course they already know everything there is to know about you, but they want to hear how you present yourself. They want to have a conversation with you, get a feel for the kind of person you are and whether it matches the environment and the culture and what they know astronauts have to do. It's like any job interview at that point: Do you fit into the job environment, which calls for well-rounded, articulate people who can work on a team, have a desire for learning, and are technically competent? They know you're technically competent by the time you get there.

RML: You joined NASA in 1996. What are the most memorable experiences, high points, low points over the 16 years that you were a member of the astronaut family?

MAGNUS: Oh my gosh, I could go on for hours. I got to do so much more than I ever expected because I went in just thinking, 'I want to fly in space.' There's so much more to being an astronaut than flying in space. But that really is spectacular and clearly a high point. Visiting on a shuttle and being engaged in a short-term sprint kind of mission versus living in space and being involved in more of a marathon, steady-pace kind of a mission—those are two totally different experiences and I'm very fortunate to have had both. Being a member of the last shuttle crew—what an honor that was. And I've never been so incredibly busy—there were four of us and we had a lot of stuff to do. It was just nuts, it was like helmet fire the whole time.

Another high point was getting to fly and learning how to fly jet airplanes as a civilian. They taught us how to fly T-38s. I never expected to get to do that, because astronauts fly in space. Well, guess what? You get to fly airplanes too, and that's really cool.

I lived under water for a week in the Aquarius habitat as part of a NEEMO mission.[1] I didn't know that was involved in being an astronaut. I lived under water! That's way cool.

I got to spend a huge amount of time working with international partners by being involved in the space station. I hit the right time to be an astronaut because it was so exciting. One of my first jobs was in Russia, in 1998 just out of astronaut candidacy school. I worked with the Russians and the other international partners to set up how we're going to operate on the space station, set up the procedures, come up with the lexicon to translate words back and forth. Something that simple was really important. It was at times very frustrating, at times very challenging because we were charting new paths and forging new relationships, but also very rewarding and exciting.

Astronauts need to be well-rounded, articulate people who can work on a team, have a desire for learning, and are technically competent.

It was also really rewarding to work as a Capcom [capsule communicator] in mission control for the very start of the space station program, getting to set up procedures and help train the control room on what it takes to go from shuttle mode to station mode, where you're not sprinting and you're in a marathon.

The Columbia accident was a very low point. There were several classmates on that mission. That was really hard. But the thing that was very impressive was to see the incredibly complex, very elegant, very efficient systems engineering approach taken across all of NASA related to all aspects of that accident, to get us back to flying.

I could go on and on. It was an incredible experience. I was always learning new things, which was really fun.

[1] NEEMO = NASA Extreme Environment Mission Operations

CHF: Speaking of learning, and going back to your collaboration with the Russians, was there any language training and cultural training?

MAGNUS: I had four years of German in high school, a semester of German and a semester of Russian as an undergrad, and at Georgia Tech I took two years of German, two years of Russian, and six months of Spanish. I like languages. So I came to NASA with some Russian language and didn't have to start from scratch. I also had a Russian teacher and at least two hours a week the whole time I was there, except when I was in training and had six hours a week, although I substituted two hours of that for Japanese and I ended up studying Japanese for a year as well. I've forgotten most of that so I can't claim Japanese anymore.

CHF: Do all astronauts study Russian?

MAGNUS: All cosmonauts study English, all European astronauts study Russian (they already have English), and the Japanese, bless their hearts, they study both.

RML: Do astronauts across the globe keep in contact with one another? Do you have contact with not only the US astronauts you kind of grew up with but also the Russian cosmonauts and the other folks who were on the mission?

Technology has developed to the point that space is accessible to more people at many levels of experience.

MAGNUS: Yes. We have a professional society called the Association of Space Explorers and there's a once a year get-together. Not everybody goes every year but those of us who are still in the aerospace industry see each other. I run into Sergei Krikalev a lot. I see Jerry Ross every now and then. I see Chiaki Mukai from Japan a lot, and Takao Doi from Japan. I run into Chris Hadfield every now and then.

It's a very small community so we all know each other, and Houston has an astronaut reunion every couple of years for whoever wants to come. It's like any other set of business associates. You keep loosely in touch and then you have touch points.

RML: What fraction of the population of astronauts, cosmonauts, and the like are women?

MAGNUS: Ten percent internationally, 20 percent US.

CHF: Do you mind my asking, what prompted you to leave your dream career?

MAGNUS: This was hard. The shuttle retired and the number of people they needed to fly missions went down from 35–40 a year to 4. The shuttles required crews of 5–7 people and we flew 5–7 shuttle crews a year during the height of the shuttle program while we were assembling the space station. There are 6 people at a time on the station, where you stay for six months, so that's 12 people a year—6 Russians, and the United States has 3 or 4 of the remaining 6 slots. That's based on the memorandums of understanding established between the international partners that defines how we work together and contribute to the station.

So the US needs went down to 3 or 4 astronauts per year. Since I was on the last shuttle mission in 2011, I started reevaluating what does the rest of my career look like? I was 47 or 48 at the time. I could get back in line for the station, which at the time had a commitment from the partners to operate through 2020. I suspected that it will go longer but I only had the data to 2020. I calculated that between 2012 and 2020 there were 17 unassigned slots to fly on station. Looking around the office I could see there were more than 17 people with less flight experience than I had, and quite a few of them had never flown yet and so were probably in line ahead of me. On the other hand, I could be eligible for a station commander slot, but that might not happen until 2017, 2018, 2019. And it's possible the station will continue to 2024, which would open up some more slots. So if I stuck around long enough, I could probably fly again some time between 2017 and 2021.

If I stayed to try and fly again that meant the rest of my career would probably be at NASA, because that's a 10-year commitment—you're not done with the mission when you come home, you've got another year or so of activities related to closing out the mission. So if I'm going to fly again it's another 10 years at NASA, then I'll be 58, almost 60, and I'll retire and do something else.

I thought about that. Here's what happens when you're not training to fly and you're waiting for an assignment. You get a technical job. For example, one of my technical jobs was to go to Russia and work on getting ISS operations off the ground as I described earlier. Another was to be a Capcom. Another was to lead the return to flight for the office. For one of my technical jobs I worked with the Canadians on the special purpose dexterous manipulator robot, and for another I helped the science community design experiments. I had a variety of technical jobs over the years. I had done almost all of them.

That meant that if I was going to stay and potentially fly again, I was going to be doing work I'd already done and it wasn't going to be very challenging for me and I wasn't going to be learning. I had an assignment as deputy chief of the office; that was new and probably could have given me about 2 years of interesting and challenging work. Then I would have had 4 to 6 or 8 years of going back into the technical world doing stuff I already felt like I understood.

So I had to make a strategic decision about what was really important for my life. Do I stay here for 10 years just to fly one more time—maybe, not guaranteed—and not be in an environment where I'm challenging myself on a day-to-day basis, which makes me kind of crabby? Do I choose to be kind of unhappy on a daily basis in order to fly in space one more time which is super-wow neat!

What happens when you think about leaving is that word gets out and you start getting phone calls from people who want you to do stuff. This opportunity came up at AIAA. I had gotten other phone calls about other opportunities, none of which I thought were good (we can talk about how I decided what good or bad was in a minute), but the AIAA opportunity came up and it checked off a lot of boxes of things that I thought might be interesting to do. So it was a strategic decision but also an extremely emotional one.

I had to disconnect from my emotions because I am an astronaut. Astronauts fly in space. I always wanted to be an astronaut. It's who I am. How could I put myself in a position where I never get to go to space again? It was really hard. But in the end it was a strategic decision.

RML: AIAA is an interesting organization, from my perspective at least, in the sense of its views on the future of aerospace. What are your thoughts on that—where do you see things heading? I know there have been conversations in this country about the establishment of what would be called the US Air and Space Force to be something of a supplement to the current Air Force, and hypersonic vehicles are a part of that. Is that a likely reality or where do you see the future of space in terms of the US position?

Magnus in the cupola of the Atlantis.

MAGNUS: We can talk about the space side and the aviation side because it's all kind of linked now. Here's how I like to describe what's going on.

For 50 years the government has been investing in space—in the technologies, the workforce, the knowledge development, the equipment, the operations and understanding for how to go to space—and we finally got to a point where the baseline level of knowledge is so fundamental that college students are building cubesats and launching them and operating them out of their own mission control rooms. That was unheard of when I was in college.

That level of knowledge, the dissemination of knowledge, and the evolution of technology have all been critical to get us where we are today. Technology has developed to the point that space is accessible to more people at many levels of experience, such as college students, for example. Not only is the baseline knowledge there but also the operational experience and the vocabulary—just think about the rising tide lifting all boats, where the tide is the level of foundational knowledge and enabling technology. Couple that with the fact that there are some people with huge amounts of money who are excited about space and willing to invest in business ideas that are space related, and the result is the entrepreneurial and creative energy occurring in the industry today.

Investors feel they have enough data to build a business case—which admittedly is still murky, but the risk/reward equation is tipping toward the realization that 'hey, there's potential reward here.' So the entrepreneurial community, which tends to be more active in the US

Magnus talks with students at the Southern California FIRST LEGO League (SoCal FLL) Regional Championship, December 2013.

than anywhere else in the world, is willing to invest in it. And the government is willing to facilitate that.

So after 50 years of government investment, some nongovernmental activity is starting for all these reasons. And that's healthy, because ideally you want government investment to lead to the furthering of an industry, the founding of an industry, the creation of more jobs, and so forth.

Still, even though we've got 50 years of knowledge, and wonderful technology, and people willing to invest, this is not easy. You don't just wake up in the morning and create a space industry that's non-government-based in a day. It could take a decade, or 15 or 20 years—and we're about 5 to 7 years in.

We're in a transition period, which is actually very interesting. We're all trying to figure it out. I think of it as an expanding bubble with the government at the leading edge of the bubble. The government leads the bubble off the planet, and private industry fills in the back side of the bubble, which is now on low Earth orbit. And as private industry is doing that, government—NASA—is able to expand the bubble beyond low Earth orbit, which is exciting. We're continuing to push the frontier of human and technical knowledge and that's something government has to do.

RML: What is AIAA's role in what you're describing?

MAGNUS: AIAA's role as a professional society is to be what I would call the middle ground or the neutral ground or the facilitator. We're a place where scientists and engineers and technical people and program managers can come together and talk about the issues that affect everybody and work together on a solution. We're not a lobbying group, we're not going to lobby for a specific industry.

For example, let's look at aviation. Commercial aviation is incredibly safe, that's very well established. Now you've got the introduction of unmanned aerial vehicles (UAVs), drones. How do you integrate them into this complex air system with commercial aviation and general aviation? The same thing is happening in space. Everybody wants to launch 8,000,000 satellites. How do you incorporate that into the system and keep track of all of them? And then there's hypersonics. We'll keep pushing those technologies, but how do you incorporate all that?

A professional society is the place where the different sectors can come together to talk about issues that concern them all, not just in terms of policy but also technology development and resources. I think AIAA has a strong role to play as an enabler and a facilitator, a place to find common ground.

CHF: Looking at specifics, what are the aspects of your current job, if you can talk about them, that really wind your clock, that get you excited about being at AIAA?

MAGNUS: It goes back to when I was thinking about my future life, I had to address the question: What do you do when you've done the only thing that you ever wanted to do? That's a really tough question.

One of the pieces of advice that I give people now and that I got when I was younger is, always follow your passion. You don't ever want to do something that's not interesting to you. I knew I didn't want a job just to have a job. I wanted a job I could sink my teeth into, something I was passionate about and interested in. Being an astronaut wasn't a job to me. It was like a lifestyle or a vocation. As I was thinking of what to do next, I thought the probability that I have anything like that ever again is slim but it can happen.

But there are other things I'm passionate about and interested in, and I sat down and made a list of them. I also made a list of things I knew I didn't want to do, because that can be helpful too—sometimes it's easier to eliminate things than to come up with stuff from scratch. I also bought a map of the United States and crossed off all the places I didn't want to live because it was too cold—there were some practical parts to this as well.

What are things that I like? STEM and working with young people: very important. Again, based on my experience, you have to expose kids, students, young people to these ideas so they can know what their possibilities are, because it's difficult to choose a career if you don't know it exists.

I wanted to stay in aerospace. Eventually I might move out of aerospace, but for now I want to stay because I want to use my "astronaut silver bullet" wisely and not just for one company. That wasn't for me.

I was interested in learning how nonprofits work because some day I think it would be interesting to do humanitarian work or disaster relief. I'm not a medical person but I'm extremely organized and I can do logistics. The job I do now gives me an entrée into nonprofits and how they work in general. The AIAA position was also attractive because I can speak out on issues related to the industry.

Another thing that was attractive was that I'd never done management before. Astronauts may be leaders but we're not managers. We are not "in charge" or managing anything as part of our roles at NASA. And our leadership is sort of tangential because we don't have any official authority for products, we're the customer for lots of people: people make the equipment, we use it; people make the products, we use them.

The AIAA position was an opportunity to find out if I had management and leadership capabilities. First of all I'd find out if I have the capabilities and, second, whether I like it and want to continue doing those kinds of things. I figured if I have the capabilities and it went really well, other doors would open that I didn't even know existed.

If it went really badly I could join the Peace Corps, because that's something I want to do anyway and that would give me my out from aerospace. I'm totally serious about that and it's still an option for me.

So there was no downside to taking the AIAA position and it checked a lot of boxes. It's in Washington, DC, a nice area, not too cold—I'm really not a winter person (Moscow was hard). And this is not a permanent job—it has a time period associated with it. I was also looking at academia, which checks a lot of boxes, but at that moment when I was evaluating my future trajectory I saw academia as my final home and I wasn't ready for a final home yet. So that's why I came here. It checked a lot of boxes and I did that analysis.

RML: You mentioned education and young people and that's of great interest to the NAE as well. Do you speak to young people? What sort of interaction do you have with youngsters?

MAGNUS: I do a lot in my role as AIAA executive director. I've been going out of my way to do a lot with undergraduates, graduates, and young professionals who are at the beginning of their career. We have seven annual student paper competitions and I've been going to two a year. One is a design-build-fly competition for undergraduates and I go to that every year.

I've also been out and about talking with our section members and they sometimes have students at their meetings. We've been working on our student program conferences so that when the students come we can better engage them with the community—they get exposed to what's going on, they meet mentors and role models, and they get to meet each other because they'll be their network. Every time I talk to students, I tell them, "Look around this room. These are the people you're going to be travelling with for the next 30–35 years of your life. You need to start establishing your networks now."

I think AIAA has a strong role to play as an enabler and a facilitator, a place to find common ground.

For the younger crowd, we've been rebuilding the AIAA Foundation to set up some more concrete STEM programming. That's still in the works; we've been working on it for three years so hopefully we're going to get that off the ground. But when people ask me to come talk to kids, I really do all that I can. I get a lot of requests; I can't do all of them, but I've gone to several high schools in the area, and I talk to Girl Scout troops. Whenever I'm free and I can, I go talk to younger kids as well.

For example, after I got back from my first mission, Space Transportation System (STS) 112, I went to my hometown and probably talked to 90 percent of the high school and middle school students in the area.

RML: On another subject, I understand that you know NAE executive officer Al Romig. How did you come to know each other?

MAGNUS: When you're in the astronaut office, you're pretty isolated from the rest of the industry, although you don't realize it at the time because you're very focused on executing the missions—in my case the space station—so you only have a small sliver of a window into what's going on across the aerospace industry. When I became executive director of AIAA in late 2012, I started getting out and about in the industry a lot more and that's when I met Al. I've met a lot of people in this job actually. Al's a good guy. We hit it off.

CHF: As we approach the end of our hour, is there anything you'd like to convey to the NAE members and/or readers of the *Bridge*, who include members of Congress and students and departments of engineering around the country?

There's nothing special about me. I was a small-town girl in the Midwest with a dream and I worked really hard.

MAGNUS: I have two levels of messages. For the students: If you have a dream you can achieve it. When I was a kid, even though I knew I wanted to be an astronaut, I remember still doubting myself, thinking 'Right, like I'm going to be an astronaut. Other people get to do that. I'm just a girl from a small town.' It's very easy to talk yourself out of your dream because it seems so impossible. But the point is, there's nothing special about me. I was a little girl with a dream. I worked really hard and it happened.

You owe it to yourself to try for your dreams. If you don't try, you never get anywhere. That's a message I give students when I talk to them. There's nothing special about me. I was a small-town girl in the Midwest with a dream and I worked really hard. So that's one level of message.

CHF: That's a great message for people of all ages, actually.

MAGNUS: Yes, because people put limits on themselves. It's really easy to talk yourself out of why you shouldn't go do something because it seems too hard or what if you fail, blah, blah, blah. That's all bullcrap. You owe it to yourself to try really hard and see what happens. If you don't make it, at least you know you tried. But you don't want to look back on your life and think, 'gosh, I wonder what would have happened if I had tried to be an astronaut.' That's an insane way to live. Don't live like that.

The other message goes back to where I started: Kids can't pick careers they don't know anything about. Any kind of program or activity or outreach, by anybody—this doesn't just have to do with engineers—that gives young people an idea of what's out there for them to choose from is very powerful.

For all the people in the NAE who are engineers, reach out to five students a year. Talk about how as engineers you can change the world and make it a better place and help people.

Sometimes when we talk to people about engineering, it's all about building cool stuff—which, by the way, we do in the aerospace industry, where we also make things that help people. I think having a dialogue with young women along those lines will resonate more. Why do so many young women go into biomedical? That field is almost 50-50 men and women. For engineers and policy people, my message is that programs or outreach that can show students and young people what their possibilities are are very powerful. Because you can't choose it if you don't know it exists.

RML: Those are great messages and I'm delighted to hear that you pay so much attention to young people. I have four granddaughters and I'm always concerned about making sure they understand that this world is for them as well as for everybody else and they need to have dreams too.

CHF: And speaking of reaching out to kids and girls in particular, Sandy, do you know about the NAE's EngineerGirl website (www.engineergirl.org)? It's a really dynamic interactive site for young people—especially at the age you were when you decided you wanted to be an astronaut—who want to get information about engineering and all of their options. We would love to include you among the engineers featured as role models.

MAGNUS: I'll take a look at it. I'd be happy to participate in something like that.

RML: Sandy, thank you so much.

MAGNUS: I'm flattered that you guys wanted to chat. Hopefully the resulting article can inspire at least one kid somewhere.

NAE News and Notes

NAE Newsmakers

The US Department of State has announced that **Linda M. Abriola**, University Professor in the Department of Civil and Environmental Engineering at Tufts University, began service as a **US science envoy** in February 2016. Science envoys travel as private citizens and help inform the White House, the Department of State, and the scientific community about potential opportunities for cooperation. Dr. Abriola will focus on science, technology, engineering, and mathematics (STEM) education and engineering in the Middle East, North Africa, and South and Central Asia.

Jan Allebach, Hewlett-Packard Distinguished Professor of Electrical and Computer Engineering, Purdue University, has received the **2016 Edwin H. Land Medal** jointly awarded by the Optical Society of America and the Society for Imaging Science and Technology. The award "recognizes pioneering work empowered by scientific research to create inventions, technologies, and products." Professor Allebach was cited for "diverse contributions in development of widely used commercial halftoning algorithms for digital printing, digital image processing and color management, and also for leadership as an educator and researcher in the field of electronic imaging."

Wanda M. Austin, president and CEO of the Aerospace Corporation, received the **2016 Goddard Astronautics Award** from the American Institute of Aeronautics and Astronautics on June 15 at a ceremony in Washington. Her citation reads "For extraordinary leadership, vision, inspiration, and contributions to the nation's space programs." She is also the recipient of the second **Yvonne C. Brill Lectureship in Aerospace Engineering** (see page 79).

Gregory G. Deierlein, J.A. Blume Professor of Engineering at Stanford University, received a **Lifetime Achievement Award** from the American Institute of Steel Construction (AISC) in April during NASCC: The Steel Conference held in Orlando. The award recognizes individuals who have provided outstanding service over a sustained period of years to AISC and the structural steel design/construction/academic community.

Arthur L. Goldstein, retired chair and CEO, Ionics Incorporated, received the **Lifetime Achievement in Governance Award** from the National Association of Corporate Directors New England Chapter (NACDNE). NACDNE awards recognize independent directors of public, private, and nonprofit boards who have embraced high standards of corporate governance and who have made valuable contributions to the companies and organizations they serve. The award was presented at a ceremony on May 5 in Boston.

Leslie Greengard, director, Simons Center for Data Analysis, Simons Foundation, and professor of mathematics and computer science, Courant Institute of Mathematical Sciences, New York University, was **elected to the American Academy of Arts and Sciences** on April 20.

Antony Jameson, Thomas V. Jones Professor of Engineering at Stanford University, won the **2015 Daniel Guggenheim Medal** for his "exceptional contributions to algorithmic innovation and the development of computational fluid dynamic codes that have made important contributions to aircraft design." He received the medal at the AIAA Aerospace Spotlight Awards Gala on June 15 at the Ronald Reagan Building and International Trade Center in Washington.

Ahsan Kareem, Robert M. Moran Professor of Engineering at the University of Notre Dame, was awarded the **2015 Theodore von Karman Medal** by the American Society of Civil Engineers. The von Karman Medal is the highest national medal awarded in the field of engineering mechanics. Dr. Kareem also shared ASCE's **2015 J. James R. Croes Medal** with Seymour M.J. Spence. The Croes Medal is given to authors whose paper was particularly notable for its contribution to engineering science.

Robert S. Langer, David H. Koch Institute Professor, Massachusetts Institute of Technology, has been honored by the American Association for Cancer Research with the **2016 AACR–Irving Weinstein Foundation Distinguished Lectureship**. The presentation was made at the AACR annual meeting in New Orleans April 16–20. Dr. Langer was recognized for his groundbreaking research at the interface of biotechnology and materials science, which has led to the development of cutting-edge drug delivery systems and to seminal breakthroughs in the fields of tissue engineering and regenerative medicine.

Cato T. Laurencin, University Professor; Van Dusen Professor of Orthopaedic Surgery; professor of chemical and biomolecular engineering, of materials science and engineering, and of biomedical engineering; director, Institute for Regenerative Engineering; and director, Raymond and Beverly Sackler Center, University of Connecticut, is the 2016 recipient of the **Connecticut Medal of Technology**. He accepted the award at the 41st annual meeting and dinner of the Connecticut Academy of Science and Engineering on May 24. Connecticut governor Daniel P. Malloy cited Dr. Laurencin's "internationally recognized work developing revolutionary technologies using his combined background in medicine and engineering. In addition, we honor Dr. Laurencin's success both as an inventor and as someone who creates environments that allow innovation to grow."

NAE members **Richard A. Meserve** (cochair), president emeritus, Carnegie Institution for Science, and **Venkatesh Narayanamurti**, Benjamin Peirce Professor of Technology and Public Policy, Harvard School of Engineering and Applied Sciences, and director, Science, Technology, and Public Policy Program at Harvard Kennedy School, will serve on the **Steering Committee for the Public Face of Science**, the newest project of the American Academy of Arts and Sciences. The three-year initiative will examine public attitudes toward science and identify issues that require greater attention from scholars and practitioners alike. Members of the steering committee are national leaders in communications, law, journalism, public affairs, and the physical, social, and life sciences.

Gordon E. Moore, retired chair of Intel Corporation, is the recipient of the **2016 Inaugural Thomas Jefferson Foundation Medal in Global Innovation**. The University of Virginia and the Thomas Jefferson Foundation jointly present the medal to recognize the achievements of those who embrace endeavors in which Jefferson excelled. The medal is the highest external honor bestowed by the university, which grants no honorary degrees.

The **Leader of Innovation Medal** was presented by Philadelphia University to **Celestino R. Pennoni**, chairman of the board, Pennoni Associates Inc. Consulting Engineers. The awards ceremony was held May 7 in Philadelphia.

Simon Ramo, cofounder, TRW Inc., became the oldest person to receive a US patent. Patent number 8,606,170, issued in late 2013, is a computerized, hub-and-spoke learning system for use in regular classrooms. Dr. Ramo received the patent at the age of 100.

The Association for Computing Machinery's Council on Women in Computing named **Jennifer Rexford**, Gordon Y.S. Wu Professor in Engineering, Princeton University, as the **2016–2017 Athena Lecturer**. Professor Rexford was cited for innovations that improved the efficiency of the border gateway protocol (BGP) in routing Internet traffic, for laying the groundwork for software-defined networks (SDNs), and for contributions in measuring and engineering IP networks.

Joan B. Rose, Homer Nowlin Chair in Water Research, Michigan State University, has won the **2016 Stockholm Water Prize**. She was chosen for her tireless contributions to global public health: in assessing risks to human health in water and creating guidelines and tools for decision makers and communities to improve global health. H.M. King Carl XVI Gustaf of Sweden, Patron of the Stockholm Water Prize, will present the prize at a ceremony on August 31, during the 2016 World Water Week in Stockholm.

Pentagon officials announced that **Alan E. Willner**, Steven and Kathryn Sample Chair in Engineering, University of Southern California, was chosen as one of the **2016 class of National Security Science and Engineering Faculty Fellows**. The program awards grants to top-tier researchers from US universities to conduct long-term, unclassified, basic research of strategic importance to the Defense Department.

Paul Zia, Distinguished University Professor Emeritus, North Carolina State University, shared the **Charles S. Whitney Medal** with Gary J. Klein, Sami Gregory W. Lucier, and Hanna Rizkalla. The American Concrete Institute presented the award "for their analytical and experimental research studies at North Carolina State University that have led to significant advances in design of precast structures, especially precast members used in parking structures."

US News & World Report announced **STEM Leadership Hall of Fame** inductees, who were honored at the *US News* STEM Solutions conference May 18–20 in Baltimore. Honorees are leaders who have achieved measurable results in the STEM fields; challenged established processes and conventional wisdom; inspired a shared vision; and motivated aspiring STEM professionals. Two of the five honorees for 2016 are NAE members: **Ellen J. Kullman**, retired chair of the board and CEO, E.I. du Pont de Nemours and Co., and **John J. Tracy**, chief technology officer and senior vice president, Engineering, Operations, and Technology, the Boeing Company.

The National Ethnic Coalition of Organizations (NECO) is the sponsor of the **Ellis Island Medals of Honor**, presented each year on historic Ellis Island to a select group of individuals whose accomplishments in their field and inspired service to our nation are cause for celebration. The medal recognizes individuals who have made it their mission to share with those less fortunate their knowledge, courage, compassion, talents, and generosity, while maintaining the traditions of their ethnic heritage as they uphold the ideals and spirit of America. NAE members who received the 2016 Ellis Island Medal of Honor are **Paul G. Gaffney II**, president emeritus, Monmouth University; **Leroy E. Hood**, president, Institute for Systems Biology; **Asad M. Madni**, independent consultant and retired president, chief operating officer, and CTO, BEI Technologies, Inc.; and **C.L. Max Nikias**, president, University of Southern California.

NAE Honors 2016 Draper Prize Winner

Left to right: Franklin C. Miller, C. D. Mote, Jr., Andrew J. Viterbi, and Charles O. Holliday, Jr.

Andrew J. Viterbi was awarded the 2016 Charles Stark Draper Prize for Engineering "for development of the Viterbi algorithm, its transformational impact on digital wireless communications, and its significant applications in speech recognition and synthesis and in bioinformatics." He was honored at a black-tie dinner with more than 90 guests on February 16 at the National Academy of Sciences building in Washington, DC. NAE President **C. D. Mote, Jr.** and Council Chair **Charles O. Holliday, Jr.** presided, and the Honorable Franklin C. Miller, chair of the board of directors of Draper, assisted in the presentation.

Charles Stark Draper Prize for Engineering

Dr. Viterbi has spent his career in digital communications. In 1966 he created the Viterbi algorithm, used today by mobile phones throughout the world for channel decoding as well as most digital satellite communications systems. The algorithm helped usher in the age of cell phones by identifying the most likely computing paths, thus making it easier to eliminate static in transmissions.

Now utilized in mobile communications, cable, DSL modems, and Ethernet, the algorithm is critical to multiple disciplines and applications—for example, it enables greater signal strength in communications on deep space missions and plays a significant role in genetic sequencing.

Dr. Viterbi is president of the Viterbi Group, which advises and invests in startups in digital and wireless communications. As cofounder of Linkabit in 1968 and Qualcomm in 1985 he led the development of innovative technologies based on code division multiple access (CDMA). He was also a professor at the UCLA School of Engineering and Applied Science (1963–1973) and then taught part-time at the University of California, San Diego, where he has been professor emeritus since 2004.

His numerous awards and honors include the IEEE Medal of Honor, National Medal of Science, Marconi International Fellowship Award, Benjamin Franklin Medal in Electrical Engineering, and Alexander Graham Bell Medal, as well as eight honorary doctorates. He is a member of the National Academy of Engineering, National Academy of Sciences, and American Academy of Arts and Sciences.

Dr. Viterbi studied electrical engineering at the Massachusetts Institute of Technology, earning SB and SM degrees in 1957, and the University of Southern California (USC), where he earned a PhD in 1962. In 2004 the USC School of Engineering was renamed the Viterbi School of Engineering in his and his late wife's honor.

Acceptance Remarks by Andrew J. Viterbi

Andrew J. Viterbi

A wise friend, who has received his share of recognition, commented on receiving an award that people and papers don't win prizes. Nominations and supporting letters do! So I am most grateful to the initially anonymous nominator and references who supported my nomination and, of course, equally to the selection committee that voted me worthy of such an honor.

I feel like the horse who won the Triple Crown: in my case, chronologically, the National Medal of Science, the IEEE Medal of Honor—and now the National Academy of Engineering, representing the outstanding members of our profession, has honored me with the Charles Stark Draper Prize. I'm also grateful to the Draper Laboratory, formerly known as the MIT Instrumentation Lab, which established the prize.

I never met **Doc Draper**, although I was a student during a short fraction of his lengthy distinguished career at my alma mater. That was a period of great intellectual leaders at MIT: in addition to Draper, there stood out Norbert Wiener, **Claude Shannon**, and **Bob Fano**, who created new disciplines and disciples, research groups and laboratories that pioneered the remarkable technological advances which today the public takes for granted. I chose to follow the latter three to delve into the mysteries of digital communication and information. But along the way I kept running into Doc Draper's accomplishments.

In my first professional job, at JPL in Pasadena, my section was responsible for telemetry to support radio guidance of a ballistic missile, which employed a hybrid combination of inertial and radio guidance; the inertial system of course was based on the technology invented by Doc Draper. Fast forward half a century and today's accurate real-time mapping, which we all use in our cars, for example, is performed using GPS/INS, an advanced form of hybrid inertial-radio guidance.

Even before that early phase of the space age, I had heard often of Dr. Draper's Instrumentation Lab from my best friend in both high school and college; he worked there from his graduate school days through to retirement, having concentrated along the way on space-based computing for the Apollo Lunar Program. If my friend could devote four decades to a career at the lab, it must provide a pretty stimulating technical and working environment.

If I speak much longer, this will start sounding like a Motion Picture Academy Award acceptance speech. And the only contact I've had with entertainment has been strictly of a technical kind, involving digital video compression and transmission, hardly the stuff that excites the public.

But before concluding, let me say that my greatest passion is the advancement of higher education in engineering and the sciences, certainly a priority for Dr. Draper as well. Consequently, I am turning back to the NAE the generous monetary component of the Draper Prize to be used for the purpose of advancing the engineering profession through attracting and educating the best and brightest of new generations who will become the outstanding engineers of the future.

Thanks again to the Academy, the Draper Laboratory, and all of you for coming.

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

Left to right: John C. Wall, Laurie Leshin, Kristin K. Wobbe, Richard F. Vaz, Arthur C. Heinricher, Diran Apelian, Bernard M. Gordon, and C. D. Mote, Jr.

On April 15 Diran Apelian, Arthur C. Heinricher, Richard F. Vaz, and Kristin K. Wobbe accepted the 2016 Bernard M. Gordon Prize for Innovation in Engineering and Technology Education awarded to Worcester Polytechnic Institute (WPI) "for a project-based engineering curriculum developing leadership, innovative problem solving, interdisciplinary collaboration, and global competencies."

NAE president **C. D. Mote, Jr.** presented the awards, joined onstage by **Bernard M. Gordon**, BMG Charitable Trust; Laurie Leshin, president of WPI; and committee chair **John C. Wall**, retired vice president and CTO of Cummins. The presentation concluded with remarks from Senator Harriette L. Chandler, State Senate Majority Leader; Gladys Rodriguez, senior district representative from the office of Congressman James P. McGovern; and Dr. Leshin. The public lecture will take place during the 2016 NAE annual meeting on Sunday, October 9.

The project-based engineering curriculum at WPI prepares 21st century leaders to tackle global issues through interdisciplinary collaboration, communication, and critical thinking. The institute's engineering program engages students with a specially designed sequence in which first-year students complete projects on topics such as energy and water; second-year capstones focus on the humanities and arts; junior-year interdisciplinary projects relate technology to society; and senior design projects are done in conjunction with external sponsors, providing relevant experience upon graduation. Last year, WPI launched its Institute on Project-Based Learning, an initiative to help other colleges and universities make progress toward implementing project-based learning on their campuses.

Diran Apelian, Alcoa-Howmet Professor of Mechanical Engineering and director, Metal Processing Institute, and WPI's provost from 1990 to 1997, is credited with bolstering the infrastructure needed for global programs as well as project-based learning across the campus. He led the charge to broaden WPI's academic programs by supporting faculty to reengineer engineering education and ensuring a holistic approach to learning. For the past decade he has played a pivotal role in transforming students' first-year experiences with programs such as the Great Problems Seminar where students dive into large-scale problems like the NAE Grand Challenges for Engineering. Apelian and co-recipient Heinricher are also the architects of the Grand Challenge Scholars Program at WPI.

Arthur C. Heinricher joined the faculty at WPI in 1992 and has been dean of undergraduate studies since 2008. In this capacity he is responsible for the assessment and improvement of undergraduate programs and curriculum. As a professor of mathematical sciences, he helped usher in new curriculum models such as undergraduate peer learning assistants to support team projects in introductory courses and a unified calculus-physics-humanities learning community for interdisciplinary projects. He also serves on the steering committee for WPI's Institute on Project-Based Learning, was a founding member and associate director and director for the WPI Center for Industrial Mathematics and Statistics, and helped organize WPI's Research Experience for Undergraduates in Industrial Mathematics and Statistics.

As dean of interdisciplinary and global studies, Richard F. Vaz has overseen expansion of WPI's Global Projects Program from 18 to 46 locations, while leading the charge to increase student participation in off-campus project programs. He oversees efforts to evaluate and enhance the quality of the Interactive Qualifying Project, WPI's interdisciplinary research project requirement, and directed a major study from 2012 to 2014 evaluating the long-term impacts of project work on 38 years' worth of WPI alumni. In 2015 he led the development and delivery of WPI's Institute on Project-Based Learning.

Kristin K. Wobbe, associate dean for undergraduate studies and director of WPI's Great Problems Seminar (GPS), was a significant driver of the development and implementation of first-year curriculum, participating on the committee that recommended the introduction of a first-year project experience and then in delivering one of the inaugural classes in the program. She led efforts to develop common learning outcomes and associated rubrics for programmatic assessment, and initiated a summer faculty development program for the GPS instructors in which best practices are shared, common frameworks have been developed, and community is forged. She also is a member of the steering committee for the Institute on Project-Based Learning.

Acceptance Remarks by Diran Apelian

I am humbled and honored to be here today at this celebratory event. It is my privilege to represent the recipients of this distinguished honor—WPI, our university, and my colleagues here on the stage. I also stand here on behalf of a legion of colleagues who had the courage 45 years ago to adopt a new paradigm that disrupted the norm in engineering education by introducing an outcomes-based approach to learning, *and* who had the tenacity required to keep that program alive and to continually renew it.

Diran Apelian

Thus, we—the four recipients of the award—humbly accept this honor in tribute to a remarkable community of talented and dedicated individuals. We wish to remember one colleague in particular: the first Dean of Undergraduate Studies William Grogan. During his more than 40 years at WPI, Bill helped shape the original WPI plan and was the individual most responsible for its successful implementation and growth. Our only wish is that he could have been with us today.

WPI is being recognized for what we have accomplished, and it is indeed a proud day for our *entire* community. What we—collectively—have done is quite remarkable.

- We practice active learning.
- We inspire our young women and men to make a difference by being part of the solution in tackling the most important challenges our society faces.
- We ensure that our students learn to be comfortable being uncomfortable; that they can tackle fuzzy situations where the problems are not well defined.
- We encourage our students to work in teams so they learn the benefits of collaboration and the value of collective impact.
- We provide transformational experiences and opportunities for our students. We have established more than 42 global sites where our students are immersed in another culture while doing their projects in their third year. The human dimension and the social implications of technological solutions are not foreign to our students.

In closing we thank the NAE and Mr. Gordon for this extraordinary recognition.

I am certain that I speak for my colleagues and the whole WPI community when I say that this award ensures that we will continue to innovate and work for change in engineering education. This is a critical time for higher education in America, and many colleges and universities are struggling to solve problems ranging from cost of higher education, access, and inclusivity to sustainability and security. The Gordon Prize has been and will continue to be one of the strongest forces for innovation far into the future. Thank you.

2016 National Meeting

Students gather around speaker Claus Daniel.

NAE members and guests gathered at the Beckman Center in Irvine, California, on February 11 for the 2016 NAE National Meeting, which was held in honor of Thomas F. Budinger, retiring NAE home secretary. The meeting was preceded by a members' only business session from 11:00 am to noon, after which the members were joined by 200 students—from High Tech High, Cabrillo High School, Katella High School, and King Drew Magnet High School, as well as the University of California, Irvine (UCI)—for lunch and a symposium.

NAE president **Dan Mote, Jr.**, welcomed the members, guests, and students to the symposium with brief remarks encouraging the students to consider the impact they can have on the world through a career in engineering. He introduced Dr. Budinger, and thanked him for his service to the NAE and the NRC. He noted to the students that Tom had been an engineer on land, under water, and in space. Dr. Budinger talked about his early career when he destroyed icebergs, and then introduced keynote speaker **Richard Meserve**. His presentation addressed the need for considering all possible energy sources to meet the challenge for more energy.

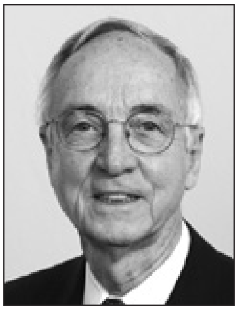
The program, chaired by Dr. Mote, continued with the Armstrong Endowment for Young Engineers–Gilbreth Lectures on issues related to energy, presented by early-career engineers who had participated in the NAE's Frontiers of Engineering symposia. Shwetak Patel, Washington Research Foundation Entrepreneurship Endowed Professor in Computer Science and Engineering and Electrical Engineering, University of Washington, spoke on "New Approaches to Sensing in the Home." Claus Daniel, deputy director, Sustainable Transportation Program, Oak Ridge National Laboratory, spoke on "Lithium Ion Batteries and Their Manufacturing Challenges." Vijay Janapa Reddi, assistant professor, Department of Electrical and Computer Engineering, University of Texas at Austin, spoke on "From Moore's Law to Moore's Crawl: Architecting the Next Generation of Mobile Computing Devices." Rebecca Moore, director of engineering, Google Earth, Earth Engine, Earth Outreach, spoke on "Google Earth Engine: A New Platform for Global-Scale Disaster Risk Resilience."

The program concluded with a presentation by Joseph V. Minervini, assistant director, Plasma Science and Fusion Center, and Senior Research Engineer, Nuclear Science and Engineering Department, Massachusetts Institute of Technology, on "Smaller and Sooner: Fusion Power on the Grid in Time to Make a Difference".

The day ended with a reception for members and guests.

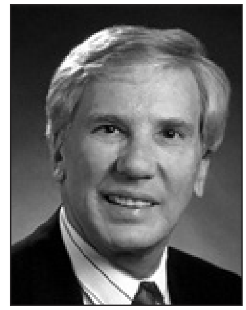
Students were invited to comment on their experience at the meeting.

Chair, Home Secretary, and Councillors Elected


Gordon R. England


Julia M. Phillips

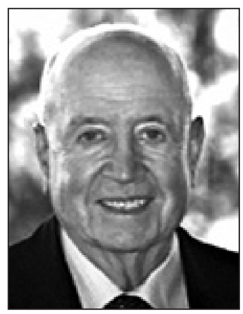

David E. Daniel


C. Paul Robinson


Josephine Cheng


Alan I. Taub


Charles O. Holliday, Jr.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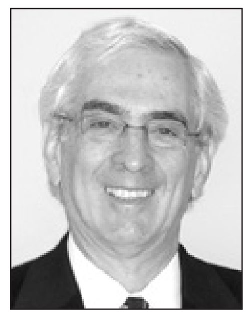
Paul Citron


Uma Chowdhry

This spring the NAE elected its chair and home secretary, reelected two incumbent councillors, and elected two new councillors. All terms begin July 1, 2016.

Elected to a two-year term as NAE chair was **Gordon R. England**, chair of PFP Cybersecurity and former president of General Dynamics Fort Worth Aircraft Company (later Lockheed Corporation). Elected to a four-year term as home secretary was **Julia M. Phillips**, retired vice president and chief technology officer, Sandia National Laboratories. **David E. Daniel**, deputy chancellor, the University of Texas System, and **C. Paul Robinson**, president emeritus, Sandia National Laboratories, were reelected to three-year terms as councillors. Newly elected to three-year terms as councillors were **Josephine Cheng**, entrepreneur and retired vice president at International Business Machines Corporation, and **Alan I. Taub**, professor of materials science & engineering and mechanical engineering at the University of Michigan and retired vice president for global research and development at General Motors.

On June 30, 2016, **Charles O. Holliday, Jr.**, chairman of the board of Royal Dutch Shell and retired chairman of the board and CEO of E.I. Du Pont de Nemours and Co., completed two terms of service as NAE's chair, the maximum allowed under the academy's bylaws. **Thomas F. Budinger**, professor of the Graduate School, University of California, Berkeley, and senior consulting scientist, E.O. Lawrence Berkeley National Laboratory, completed two terms of service as home secretary, the maximum allowed under the academy's bylaws. **Paul Citron**, retired vice president of technology policy and academic relations, Medtronic, Inc., completed six continuous years of service as councillor, the maximum allowed under the academy's bylaws. **Uma Chowdhry**, former chief science and technology officer of E.I. Du Pont de Nemours and Co., served one three-year term as councillor and chose not stand for reelection. In May, Mr. Holliday, Dr. Budinger, Mr. Citron, and Dr. Chowdhry were recognized for their distinguished service and other contributions to the NAE.

2016 Yvonne C. Brill Lectureship in Aerospace Engineering

The American Institute of Aeronautics and Astronautics (AIAA) is pleased to announce that it has selected **Wanda M. Austin**, president and CEO of the Aerospace Corporation, as the recipient of the second Yvonne C. Brill Lectureship in Aerospace Engineering. Dr. Austin will present her lecture, "Engineering Leadership: The Need for Technical Excellence and Diversity," on Thursday, September 15, in conjunction with the AIAA Space and Astronautics Forum and Exposition (AIAA SPACE 2016) at the Long Beach (CA) Convention Center.

The Yvonne C. Brill Lectureship in Aerospace Engineering was established by the AIAA with the participation and support of the NAE in memory of **Yvonne C. Brill** (1924–2013), pioneering rocket scientist, NAE member, and AIAA honorary fellow. Ms. Brill is best known for developing a revolutionary propulsion system, the hydrazine/resistojet propulsion system that remains the industry standard for geostationary satellite station keeping. In the last quarter-century of her life, she dedicated a large part of her time to helping others pursue careers in engineering, science, and mathematics and to ensuring that professional women are given the recognition they deserve.

NAE Regional Meeting Hosted by the National Renewable Energy Laboratory: "Innovation in Our Energy System"

NREL researcher Dane Christensen leads NAE members on a tour of the Energy Systems Integration Facility (ESIF) during the regional meeting. Photo by Dennis Schroeder/NREL.

On April 28 NAE members and guests in Colorado and the region gathered in the Research Support Facility at the US Department of Energy's National Renewable Energy Laboratory (NREL) in Golden to learn about the latest energy system innovations at the NAE regional meeting and symposium.

NAE president **C. D. Mote, Jr.** addressed NAE members at a luncheon and business meeting, followed by the public symposium, hosted for the first time by NREL. New lab director Martin Keller, a microbiologist who succeeded **Dan Arvizu** in December 2015, welcomed the NAE and emphasized the need for more innovation in science and engineering. He also acknowledged another of his predecessors, retired Vice Admiral **Richard Truly**, who was in the audience.

Dr. Keller noted that NREL focuses on ensuring world-class science and engineering, and shares with the other national labs a mission to conduct cutting-edge research. He explained that the labs can't close all the gaps alone, which is why NREL partners with other labs as well as universities and others. The lab is also leveraging its strengths across disciplines—for example, recently combining expertise in solar and biology—to come up with innovations. He told the audience that work in clean energy is just beginning.

Al Romig, NAE executive officer, called attention to three Academies reports relevant to the topics being discussed in the area of climate and environment: *America's Climate Choices* (2011), *America's Energy Futures* (2010), and the *National Climate Assessment* (2014).

Sam Baldwin, DOE chief technology officer, gave an overview of how DOE is looking to take advantage of new technology to make the

US electric grid more modern, resilient, and responsive.

Before an audience of more than 100, Dr. Romig moderated a panel on “The Role of Technology Innovation in our Energy System.” Dr. Keller, with three NREL associate lab directors—Bill Tumas of Materials & Chemical Science and Technology, Adam Bratis of BioEnergy Science & Technology, and Bryan Hannegan of Energy Systems—reviewed the current challenges to and state of the clean energy field, and described some exciting opportunities.

Dr. Keller explained that one reason to continue research to expand use of renewable energy is that there is much more potential for options such as wind energy, for example, which requires new materials and solutions. Just as Henry Ford’s Model T surpassed horse power, innovation didn’t stop there! So, too, in the realm of renewable energy, further development will depend on continuing innovation.

Dr. Tumas reported that advances in solar technology, now about a $100 billion business globally, have cut costs—and there is room for more on the grid. Some trajectories show that solar could be 25–30 percent of the grid mix and further enhance efforts to mitigate climate change. The evolution of solar power from megawatts to gigawatts is a positive development, but it needs to get to terawatts. And energy storage and grid reliability are important, as is understanding systems and integrating the grid.

According to Dr. Bratis, innovation in transportation is crucial. Progress in sustainability could involve a combination of electric vehicles, fuel cell vehicles, and biofuels for combustion engines. For the latter, researchers are working to find ways to transform biomass into more kinds of useful fuel precursors.

Dr. Hannegan presented a holistic perspective on energy generation. The existing rigid infrastructure needs more flexibility, but it won’t come without a hefty price tag: It’s estimated that it would cost $1 trillion in the United States alone to upgrade the grid. He noted that the Internet of Things can build a bridge to the future.

In the afternoon session, moderated by Associate Lab Director Robin Newmark, panelists discussed the role of policy, technology, and finance in transforming the energy system. Former Colorado Gov. Bill Ritter, now director of the Center for the New Energy Economy at Colorado State University, explained that a triangle of policy, technology, and financing has been the model for understanding change in the power system. Recently stakeholders, for example from regional groups of states, have been convening to take steps toward the decarbonization of power sources.

Roger Ballentine, a former White House advisor who is president of Green Strategies, Inc., said that the old grid system was like a 2D black-and-white linear system now being replaced by a 3D hologram. Change will accelerate as the millennial generation gains more impact with its IT savvy.

Susan Tierney, a senior advisor with the Analysis Group and former DOE assistant secretary who chairs NREL’s External Advisory Board, said that while there probably will never be a national energy policy for a number of reasons, policy choices can help stimulate clean energy innovation over a carbon-emitting system.

Dr. Mote closed the session, remarking that much of what he heard was new to him and that the progress in renewable energy was significant—and inspiring for the future.

“Earned Optimism”: MIT Hosts NAE Regional Meeting

Aluminum fuel fizzled. A computer crash was caught in real time. A benign copper strip revealed its secret identity as a superconductor essential for practical fusion.

At the National Academy of Engineering (NAE) regional meeting on April 14 **Ian A. Waitz**, dean of engineering at MIT, promised attendees “a window into the labs at MIT.” It turned out to be a wide-open one. The faculty-led public symposium highlighted the often hard to believe, but very real, advances happening around the Cambridge-based campus.

“Hey atoms, how well are you doing for me?” asked Jeffrey Grossman. The answer: very well indeed, thanks to a new class of self-assembled materials such as graphene. His lab uses them to improve energy storage two- and even threefold and to create better methods for seawater desalination.

Polina Anikeeva showed off a nearly noninvasive way to treat neurological disorders with multifunction fiber optics. Created by arranging the desired channels for drugs and electrodes, these larger “preforms” are then stretched into hair-like strands ready for

Grant Stokes (NAE), head, Space Systems and Technology Division, MIT Lincoln Laboratory; Jean Sack, technical staff, MIT Lincoln Laboratory's Energy Systems Group; MIT president Rafael Reif (NAE); Bob Shin, head, Intelligence, Surveillance, and Reconnaissance and Tactical Systems Division and director of Beaver Works at MIT. Photo courtesy of MIT.

implantation. "They look and act almost like the brain's own neurons," she observed.

While not organized around the NAE Grand Challenges for Engineering, many of its themes—energy, water, cybersecurity, and health and medicine—were addressed by the MIT speakers, aptly reflecting the enduring power and flexibility of the now famed calls to action. In his opening remarks, MIT president **Rafael Reif** spoke to that point, calling the Grand Challenges a "beautiful way to capture the entire profession of engineering."

NAE president **C. D. Mote, Jr.** took that sentiment a step further. He encouraged institutions to integrate solving the challenges into academic curricula, rather than primarily addressing them in labs.

Noting an earlier overview of MIT's educational innovations presented by Dr. Waitz, Dr. Mote lauded the institution's philosophy of "following the passion of [its] students." He said that MIT is doing "something special" because students arrive eager to tackle the big problems.

In fact, that specialness was seen firsthand. Jean Sack of the MIT Lincoln Laboratory wowed the crowd by demonstrating aluminum-based fuel that has been created by students as part of a design challenge for underwater vehicles. Dennis Whyte, head of nuclear science and engineering, praised a group of his students who, "not knowing it was impossible," designed a compact, practical fusion nuclear energy reactor. Microthruster technology, created by Paulo Lozano's group to propel small satellites using jets of ion beams, inspired MIT alumni to create a new aerospace company.

In true form, MIT did bring out a few examples that seemed almost on par with the school's well-known "hacks."

Chris Voigt demonstrated a programming language for cells that coaxed bacteria into displaying the digits 0–9, akin to old LCD calculators. Dina Katabi showed how she was coopting common wi-fi signals to create imaging technologies that can see through walls and even identify those behind them. Russ Tedrake showed a movie of drones that could fly through dense forest like birds do, darting and diving out of the way of objects in real time. And Kristala Prather, a chemical engineer, described the outlook that fueled her work building microbial factories. She articulated an attitude that, in a larger sense, applied to the other presenters and, by extension, to engineering as well: "earned optimism."

In Memoriam

GEORGE H. BORN, 76, professor of aerospace engineering sciences and director emeritus, Colorado Center for Astrodynamics Research, University of Colorado Boulder, died January 21, 2016. Dr. Born was elected to the NAE in 2004 for contributions to satellite orbit determination and for applications of satellites to geophysics and oceanography.

PER V. BRUEL, 100, president, Bruel Acoustics, died April 2, 2015. Dr. Bruel was elected to the NAE in 1979 for development and production of precision acoustical and vibrational measuring instruments.

JOHN W. CAHN, 88, retired materials scientist, Department of Physics, University of Washington, died March 14, 2016. Dr. Cahn was elected to the NAE in 1998 for work on the kinetics and thermodynamics of phase transformations, interfacial phenomena, and quasi-crystals.

MICHAEL M. CARROLL, 79, Burton J. and Ann M. McMurtry Professor in Mechanical Engineering and Computational and

Applied Mathematics at Rice University and former dean of its George R. Brown School of Engineering, died January 7, 2016. Dr. Carroll was elected to the NAE in 1987 for unique contributions in the development of physically based models for geological materials and in related applications to the mechanics of porous materials.

STUART W. CHURCHILL, 95, Carl V.S. Patterson Professor Emeritus of Chemical Engineering, University of Pennsylvania, died March 24, 2016. Dr. Churchill was elected to the NAE in 1974 for contributions to chemical engineering, specifically heat transfer and combustion.

WESLEY A. CLARK, 88, principal, Clark, Rockoff and Associates, died February 22, 2016. Mr. Clark was elected to the NAE in 1999 for the design of early computers.

DAVID A. DORNFELD, 66, Will C. Hall Family Professor of Engineering and director, Laboratory for Manufacturing and Sustainability, University of California, Berkeley, died March 27, 2016. Dr. Dornfeld was elected to the NAE in 2013 for contributions to sustainability in advanced manufacturing, sensors, and precision material processing.

SOLOMON W. GOLOMB, 83, Andrew and Erna Viterbi Professor of Communications and Distinguished University Professor, University of Southern California, died May 1, 2016. Dr. Golomb was elected to the NAE in 1976 for contributions to space communications and information processing technology.

ANDREW S. GROVE, 77, senior advisor to executive management, Intel Corporation, died March 21, 2016. Dr. Grove was elected to the NAE in 1979 for leadership in semiconductor technology, particularly in contributions to the understanding of structure and instabilities of the silicon-oxide interface.

KARL A. GSCHNEIDNER JR., 85, Anson Marston Distinguished Professor, Department of Materials Science and Engineering, Iowa State University, and chief scientist, Critical Materials Institute, Ames Laboratory, died April 27, 2016. Dr. Gschneidner was elected to the NAE in 2007 for contributions to the science and technology of rare-earth materials.

LARRY L. HENCH, 77, University Professor of Engineering, Florida Institute of Technology, and professor emeritus, University of Florida and Imperial College London, died December 16, 2015. Dr. Hench was elected to the NAE in 2000 for the development of bioactive glasses for human prostheses and fundamental studies of glass corrosion.

ALFRED E. MANN, 90, chair and co-chief executive officer, MannKind Corporation, died February 25, 2016. Mr. Mann was elected to the NAE in 2001 for innovations and entrepreneurship in cardiac pacing technology, insulin delivery, and neural prostheses.

EDWARD J. MCCLUSKEY, 86, professor of electrical engineering and computer science and director, Center for Reliable Computing, Stanford University, died February 13, 2016. Dr. McCluskey was elected to the NAE in 1998 for logic design, computer engineering, and engineering education.

JOAN L. MITCHELL, 68, fellow and master inventor, InfoPrint Solutions Company, and retired fellow, IBM Corporation, died December 2, 2015. Dr. Mitchell was elected to the NAE in 2004 for leadership in setting standards for the formation of photographic fax and image compression.

EMIL PFENDER, 90, professor emeritus of mechanical engineering, University of Minnesota, died January 28, 2016. Dr. Pfender was elected to the NAE in 1986 for pioneering contributions to arc technology, plasma chemistry, and heat transfer, and for inspiration and international dissemination of knowledge.

JOHN A. QUINN, 83, Robert D. Bent Professor Emeritus, Chemical and Biomolecular Engineering, University of Pennsylvania, died February 8, 2016. Dr. Quinn was elected to the NAE in 1978 for pioneering research in mass transfer, particularly phenomena associated with transport through interfaces and membranes.

STEVEN B. SAMPLE, 75, president emeritus, University of Southern California, died March 29, 2016. Dr. Sample was elected to the NAE in 1998 for contributions to consumer electronics and leadership in interdisciplinary research and education.

Calendar of Events and Meetings

July 14	Fritz J. and Dolores H. Russ Prize Committee Meeting
August 2–3	Online Ethics Center (OEC) Advisory Committee Meeting
August 3–4	NAE Council Meeting Woods Hole, Massachusetts
September 9	Bernard M. Gordon Prize Committee Meeting
September 19–21	US Frontiers of Engineering Irvine, California
September 25–28	Frontiers of Engineering Education Irvine, California
OCTOBER 9–10	**2016 NAE ANNUAL MEETING**

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

Publications of Interest

The following reports have been published recently by the National Academy of Engineering or the National Academies of Sciences, Engineering, and Medicine. 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 (*www.nap.edu*) or by phone (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.*

Frontiers of Engineering: Reports on Leading-Edge Engineering from the 2015 Symposium. This volume presents papers from at the National Academy of Engineering's 2015 US Frontiers of Engineering Symposium, held September 9–11 at the Beckman Center in Irvine, California. The session topics were Cybersecurity and Privacy, Engineering the Search for Earth-Like Exoplanets, Optical and Mechanical Metamaterials, and Forecasting Natural Disasters. The annual symposium brings together 100 outstanding young leaders in engineering to share their cutting-edge research and innovations in selected areas.

NAE member **Robert D. Braun**, David & Andrew Lewis Professor of Space Technology, Georgia Institute of Technology, chaired the organizing committee. Paper, $49.00.

Grand Challenges for Engineering: Imperatives, Prospects, and Priorities—Summary of a Forum. In 2008 a committee of distinguished engineers, scientists, entrepreneurs, and visionaries set out to identify the most important, tractable engineering system challenges that must be met in this century for human life as we know it to continue on this planet. For the forum at the National Academy of Engineering's 2015 annual meeting, 7 of the 18 committee members who formulated the Grand Challenges for Engineering reflected on what has happened in the seven years since. This report summarizes the forum presentations and discussions.

Forum panelists who are NAE members are **Alec Broers**, UK House of Lords; **Farouk El-Baz**, director, Center for Remote Sensing, and Research Professor, Boston University; **Wesley Harris**, Charles Stark Draper Professor of Aeronautics and Astronautics, Massachusetts Institute of Technology; and **Dean Kamen**, president, DEKA Research and Development Corporation. Paper, $27.00.

TRB Special Report 317: The Essential Federal Role in Highway Research and Innovation. This report summarizes conclusions and advice on the critical role of the Federal Highway Administration (FHWA) in highway research, development, and technology (RD&T) that have been developed over the years by TRB's Research and Technology

Coordinating Committee (RTCC). The RTCC concludes that FHWA plays an essential role in exploratory, advanced research; addresses national priorities that other highway RD&T programs do not; and facilitates adoption of innovations at the state and local levels through technology transfer. The RTCC notes that FHWA will play a particularly important role in ensuring the standardization of safety alerts to motorists between infrastructure and vehicles as part of the national connected vehicle initiative and in assisting transportation agencies in implementing the many innovations developed in the second Strategic Highway Research Program (SHRP 2).

NAE member **Kumares C. Sinha**, Edgar B. and Hedwig M. Olson Distinguished Professor of Civil Engineering, Purdue University, was a member of the study committee. Free PDF.

Enhancing Participation in the US Global Change Research Program. The US Global Change Research Program (USGCRP) is a collection of 13 federal entities charged by law to help the United States and the world to understand, assess, predict, and respond to human-induced and natural processes of global change. The USGCRP has increasingly focused on research that can inform decisions to cope with current climate variability and change, to reduce the magnitude of future changes, and to prepare for changes projected over coming decades. But the breadth and depth of research in these agencies is insufficient to meet the country's needs, particularly to support decision makers. This report provides a rationale for evaluating program membership and capabilities and identifying potential new agencies and departments to enable the program to more effectively inform the public and prepare for the future. It also recommends adjustments to methods and procedures that will allow the program to better meet its stated goals.

NAE member **Warren M. Washington**, senior scientist, Climate Change Research Section, Climate and Global Dynamics Division, National Center for Atmospheric Research, chaired the study committee. Paper $39.00.

Continuity of NASA Earth Observations from Space: A Value Framework. NASA's Earth Science Division (ESD) conducts satellite and suborbital missions to observe Earth's land surface and interior, biosphere, atmosphere, cryosphere, and oceans as part of a program to improve understanding of Earth as an integrated system. Earth observations enable critical scientific advances, and environmental data products derived from these observations are used in resource management and for applications such as weather forecasts, climate projections, sea level change, water management, disease early warning, agricultural production, and response to natural disasters. As the complexity of societal infrastructure and its vulnerability to environmental disruption increases, the demands for deeper scientific insights and more actionable information continue to rise. To serve these demands, the ESD must optimize the allocation of its resources between support for measurement continuity of data streams that are critical components of Earth science research programs and the development of new measurement capabilities. This report seeks to establish a more quantitative understanding of the need for measurement continuity and the consequences of measurement gaps.

NAE members on the study committee were **Byron D. Tapley** (chair), Clare Cockrell Williams Centennial Chair, and director, Center for Space Research, University of Texas; **Michael D. King** (vice chair), senior research scientist, Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, and senior scientist emeritus, NASA; **Rafael L. Bras**, provost and executive vice president for academic affairs, Georgia Institute of Technology; **Robert E. Dickinson**, professor of geosciences, Department of Geological Sciences, University of Texas at Austin; and **Lee-Lueng Fu**, JPL Fellow, Jet Propulsion Laboratory. Paper, $52.00.

Immigration Policy and the Search for Skilled Workers: Summary of a Workshop. The market for high-skilled workers is becoming increasingly global, as are the markets for knowledge and ideas. High-skilled immigrants in the United States represent a much smaller proportion of the workforce than they do in countries such as Australia, Canada, and the United Kingdom, but they have an important role in spurring innovation and economic growth in all countries and filling shortages in the domestic labor supply. This report summarizes the proceedings of a fall 2014 workshop on the use of immigration policy to attract and retain foreign talent. Participants compared policies on encouraging migration and retention of skilled workers, attracting qualified foreign students and retaining them post-graduation, and input by states or provinces in immigration policies to add flexibility in countries with regional employment differences, among other topics. They also discussed how immigration policies have changed over time in response to undesired labor market outcomes and whether there was sufficient data to measure those outcomes.

NAE member **Subhash C. Singhal**, Battelle Fellow Emeritus, Pacific Northwest National Laboratory, was a member of the study committee. Paper, $55.00.

Review of the 21st Century Truck Partnership: Third Report. The 21st Century Truck Partnership (21CTP) works to reduce fuel consumption and emissions, increase heavy-duty vehicle safety, and support research, development, and demonstration to initiate commercially viable products and systems. This report builds on the Phase 1 and 2 reviews and reports, and comments on changes and progress since the Phase 2 report was issued in 2012.

NAE members on the study committee were **Thomas M. Jahns**, Grainger Professor of Power Electronics and Electrical Machines, University of Wisconsin–Madison; **Bernard I. Robertson**, retired senior vice president, Engineering Technologies and Regulatory Affairs, and general manager, Truck Operations, DaimlerChrysler Corporation; **Hratch G. Semerjian**, former chief scientist, National Institute of Standards and Technology; **Subhash C. Singhal**, Battelle Fellow Emeritus, Pacific Northwest National Laboratory; and **Kathleen C. Taylor**, retired director, Materials and Processes Laboratory, General Motors Corporation. Paper, $65.00.

Analytic Research Foundations for the Next-Generation Electric Grid. For the vast majority of people electricity is obtained from large, interconnected power grids. But the grid that was developed in the 20th century and incremental improvements made since then are no longer adequate. The next-generation electric grid must be more flexible, resilient, and able to accommodate a wider mix of more intermittent generating sources such as wind and distributed solar photovoltaics. Achieving this grid of the future will require continued shorter-term engineering R&D, building on the existing analytic foundations for the grid, as well as more fundamental research to expand these foundations. This report provides guidance on longer-term critical areas for the mathematical and computational sciences research needed for the next-generation grid, with recommendations to help direct future research as the grid evolves and to give the nation's R&D infrastructure the tools it needs to effectively develop, test, and use this research.

NAE members on the study committee were **Thomas J. Overbye** (cochair), Fox Family Professor, Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign; **Anjan Bose**, Regents Professor and Distinguished Professor of Electric Power Engineering, School of Electrical Engineering and Computer Science, Washington State University; **Terry Boston**, president and CEO, Terry Boston LLC; **Frank P. Kelly**, professor of mathematics systems and master, Christ's College Statistical Laboratory, University of Cambridge; **Ralph D. Masiello**, industry advisor, Quanta Technology LLC; and **Margaret H. Wright**, Silver Professor of Computer Science, Courant Institute of Mathematical Sciences, New York University. Paper, $75.00.

Mainstreaming Unmanned Undersea Vehicles into Future US Naval Operations. At the request of the former chief of naval operations, an expert committee was appointed to assess the potential of unmanned undersea vehicles (UUVs) in enhancing future US naval operations. The Department of the Navy has determined that the final report prepared by the committee is restricted in its entirety under exemption 3 of the Freedom of Information Act (5 USC §552(b)(3)) and therefore cannot be made available to the public. This abbreviated report provides background information on the full report and the committee that prepared it.

NAE members on the study committee were **Archie R. Clemins**, president, Caribou Technologies Inc., and US Navy, retired; **Charles R. Cushing**, president, C.R. Cushing & Co. Inc. Naval Architects and Marine Engineers; and **Millard S. Firebaugh**, Glenn L. Martin Institute Professor of Practice, Department of Mechanical Engineering, University of Maryland, College Park, and US Navy, retired. Free PDF.

Peer Review and Design Competition in the NNSA National Security Laboratories. The National Nuclear Security Administration (NNSA) is responsible for providing and maintaining the capabilities necessary to sustain a safe, secure, and reliable nuclear weapon stockpile for the nation and its allies. Responsibility for meeting the NNSA missions falls to the three NNSA laboratories—Los Alamos National Laboratory, Lawrence Livermore National

Laboratory, and Sandia National Laboratories—which contribute to that goal by maintaining (1) the skills and capabilities necessary for stewardship of a reliable nuclear stockpile and (2) a high level of technical credibility. Since 1992 it has been US policy not to conduct explosion tests of nuclear weapons. The resulting technical challenges have been substantial. The cessation of nuclear testing necessitated a much greater reliance on both intra- and interlab expert peer review to identify potential problems with weapon designs and define the solution space. This report assesses the quality and effectiveness of peer review of designs, development plans, engineering and scientific activities, and priorities related to both nuclear and nonnuclear aspects of nuclear weapons, as well as incentives for effective peer review. It also explores how the evolving mission of the NNSA laboratories might impact peer review processes at the laboratories that relate to nuclear weapons.

NAE members on the study committee were **Paul S. Peercy** (cochair), dean emeritus, College of Engineering, University of Wisconsin–Madison; **John F. Ahearne**, retired executive director, Sigma Xi, the Scientific Research Society; **Paul A. Fleury**, Frederick William Beinecke Professor of Engineering, and Applied Physics/professor of physics, Yale University; **Cherry A. Murray**, senior advisor to the secretary, Department of Energy; **Robert E. Nickell** (deceased), president, Applied Science & Technology; and **Steven J. Zinkle**, Governor's Chair Professor, Departments of Nuclear Engineering and of Materials Science & Engineering, University of Tennessee, Knoxville. Paper, $40.00.

Telecommunications Research and Engineering at the Institute for Telecommunication Sciences of the Department of Commerce: Meeting the Nation's Telecommunications Needs and **Telecommunications Research and Engineering at the Communications Technology Laboratory of the Department of Commerce: Meeting the Nation's Telecommunications Needs.** The Department of Commerce operates two telecommunications research laboratories at its Boulder, Colorado, campus: the National Telecommunications and Information Administration's Institute for Telecommunications Sciences (ITS) and the National Institute of Standards and Technology's Communications Technology Laboratory (CTL). ITS serves as a principal federal resource for solving the telecommunications concerns of federal agencies, state and local governments, private corporations and associations, standards bodies, and international organizations. It could provide an essential service to the nation by being a principal provider of instrumentation and spectrum measurement services, but shortages of funding, staff, and a coherent strategy limit its ability to fully function as a research laboratory. This report examines the institute's performance, resources, and capabilities and the extent to which these meet customer needs. CTL develops measurements and standards to enable interoperable public safety communications, effective and efficient spectrum use and sharing, and advanced communication technologies. Because it is new and its planned work represents a departure from that carried out by the elements of which it was composed, this study focuses on its available resources and future plans rather than past work. The Boulder telecommunications laboratories play an important role in US economic vitality and can play an even greater role given the importance of access to spectrum and spectrum sharing to the wireless networking and mobile cellular industries. Research advances are needed to ensure the continued evolution and enhancement of the connected world.

NAE members on the study committees were **Elsa M. Garmire**, Sydney E. Junkins Professor of Engineering, Dartmouth College, and **David J. Goodman**, professor emeritus, Department of Electrical and Computer Engineering, New York University. Paper, $33.00 and $32.00.

Airport Passenger Screening Using Backscatter X-Ray Machines: Compliance with Standards. In response to increased concern over terrorist attacks on aircraft, the Transportation Security Administration (TSA) has deployed security systems of advanced imaging technology (AIT) to screen passengers at airports. AITs in US airports use two types of radiation to detect threats: millimeter wave and X-ray backscatter systems. X-ray backscatter AITs were deployed in US airports in 2008 and removed by June 2013 because of privacy concerns. To address these concerns, TSA is looking to deploy a second-generation X-ray backscatter AIT equipped with privacy software to eliminate production of an image of the person being screened. This report reviews previous studies and current processes used by the Department of Homeland Security and equipment manufacturers to estimate radiation exposures resulting from backscatter X-ray AIT system use in screening air travelers. It examines whether exposures comply with applicable health and safety standards for public and occupational exposures to ionizing radiation and whether system design, operating procedures, and maintenance procedures are appropriate to prevent overexposures of travellers and operators to ionizing radiation.

NAE member **C. Kumar N. Patel**, president and CEO, Pranalytica Inc., was a member of the study committee. Paper, $69.00.

Chemistry and Engineering of Shale Gas and Tight Oil Resources Development: Workshop in Brief. Oil and gas exploration in the United States has expanded with the increased use of horizontal drilling to facilitate the recovery of shale gas and tight oil resources. The US Environmental Protection Agency estimates that 25,000–30,000 new hydraulic fracturing wells were drilled each year in 2011–2014, and the impact of those wells and the use of hydraulic fracturing have been topics of public and policy discussion. Although chemistry and chemical engineering are used extensively in the hydraulic fracturing process, their roles are not well understood outside of the oil and gas industries. At a May 2015 workshop practitioners and experts in these fields came together to discuss shale gas and tight oil resource development. This report summarizes the workshop presentations and discussions.

NAE members on the workshop organizing committee were **Robert L. Kleinberg**, Schlumberger Fellow, Schlumberger-Doll Research, and **Danny D. Reible**, Donovan Maddox Distinguished Engineering Chair, Texas Tech University. Free PDF.

SBIR at the National Science Foundation and **STTR: An Assessment of the Small Business Technology Transfer Program.** Public-private partnerships such as the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs encourage small businesses to develop new processes and products and to provide quality research in support of US government missions and they can help entrepreneurs bring new ideas to market. SBIR is particularly important because today's knowledge economy is driven in large part by the capacity to innovate. One of the defining features of the US economy is a high level of entrepreneurial activity, but converting discoveries into innovations for the market involves substantial challenges. US capacity for innovation can be strengthened by addressing those challenges. In the SBIR Reauthorization Act of 2000 Congress tasked the National Research Council with studying how the SBIR program has stimulated technological innovation and used small businesses to meet federal R&D needs and with recommending improvements to the program. The first round of the study resulted in a series of reports (2004–2009) on the SBIR program at the five federal agencies, including the National Science Foundation, responsible for 96 percent of the program's operations. This report presents a second review of the NSF SBIR program's operations. When reauthorizing the SBIR and STTR programs in 2011, Congress expanded its 2000 study mandate to include a review of the STTR program. This report builds on the methods and outcomes from the previous review of SBIR to assess the STTR program.

NAE members on the study committee were **Jacques S. Gansler** (chair), Roger C. Lipitz Chair in Public Policy and Private Enterprise and director, Center for Public Policy and Private Enterprise, School of Public Policy, University of Maryland; **Charles E. Kolb**, president and CEO, Aerodyne Research Inc.; and **Duncan T. Moore**, vice provost for entrepreneurship, Rudolf and Hilda Kingslake Professor of Optical Engineering, Institute of Optics, University of Rochester. Paper, $75.00 and $65.00.

Privacy Research and Best Practices: Summary of a Workshop for the Intelligence Community. Disclosures about the bulk collection of domestic phone call records and other signals intelligence programs have stimulated debate about the implications of such practices for the civil liberties and privacy of Americans. Many have called for the intelligence community to engage more deeply with outside privacy experts and stakeholders. At the request of the Office of the Director of National Intelligence, a workshop was convened to address the privacy implications of emerging technologies, public and individual preferences and attitudes toward privacy, and ethical approaches to data collection and use. This report summarizes the workshop discussions among experts from academia, the private sector, and the intelligence community on private sector best practices and privacy research results.

NAE member **Frederick R. Chang**, director, Darwin Deason Institute for Cyber Security, Southern Methodist University, was a member of the workshop planning committee. Paper, $40.00.

Spills of Diluted Bitumen from Pipelines: A Comparative Study of Environmental Fate, Effects, and Response. Diluted bitumen has been transported by pipeline in the United States for more than 40 years, but the amount has increased recently as a result of improved extraction technologies and higher Canadian production and exportation. Increased US importation from Canada has strained pipeline capacity and contributed to the expansion of pipeline mileage over the past five years. Rising North American crude oil production has resulted in greater transport of crude oil by rail or tanker, but pipelines continue to deliver most crude oil supplies to US refineries. This report examines the current state of knowledge and identifies the relevant properties and characteristics of the transport, fate, and effects of diluted bitumen and commonly transported crude oils when spilled in the environment. It assesses whether the differences between properties of diluted bitumen and those of other commonly transported crude oils warrant modifications to the regulations governing spill response plans and cleanup. Given the nature of pipeline operations, response planning, and the oil industry, the report's recommendations are broadly applicable to other modes of transportation as well.

NAE member **Diane M. McKnight**, professor of civil, environmental, and architectural engineering and fellow, INSTAAR, University of Colorado Boulder, chaired the study committee. Paper, $50.00.

Developing a National STEM Workforce Strategy: A Workshop Summary. The competitiveness of the United States in an increasingly interconnected global economy depends on a workforce with strong capabilities and skills in science, technology, engineering, and mathematics (STEM), and the nation needs to develop ways of ensuring access to high-quality education and training experiences for all students at all levels and for all workers at all career stages. As part of the National Science Foundation (NSF)'s responsibility for overseeing the federal government's efforts to foster the creation of a STEM-capable workforce, the Directorate on Education and Human Resources requested a workshop in support of NSF's preparation of a theoretical and evidence-based STEM Workforce Development R&D Core Framework. Participants discussed research themes, identified gaps and emerging research opportunities, and recommended refinements in the goals of the framework. This report summarizes the presentations and discussions from the workshop.

NAE members on the workshop planning committee were **Rodney C. Adkins** (chair), retired senior vice president, IBM Corporate Strategy, International Business Machines Corporation, and **Daniel E. Atkins III**, W.K. Kellogg Professor in Community Information and professor of electrical and computer engineering, University of Michigan. Paper, $54.00.

An Assessment of the National Institute of Standards and Technology Physical Measurement Laboratory: Fiscal Year 2015. The Physical Measurement Laboratory (PML) at the National Institute of Standards and Technology is dedicated to three fundamental and complementary tasks: (1) increase the accuracy of knowledge of the physical parameters that are the foundation of the modern technology-driven society; (2) disseminate technologies by which these physical parameters can be accessed in a standardized way by stakeholders; and (3) conduct research at both fundamental and applied levels to provide knowledge that may lead to advances in measurement approaches and standards. This report assesses the PML's scientific and technical work and identifies examples of accomplishments, challenges, and opportunities for improvement for each of its nine divisions.

NAE members on the study panel were **Michael Ettenberg**, principal, Dolce Technologies; **Stephen R. Forrest**, professor, Departments of Electrical Engineering and Computer Sciences, Physics and Materials Science and Engineering, University of Michigan; **James S. Harris**, James and Ellenor Chesebrough Professor, Department of Electrical Engineering, Stanford University; **Max G. Lagally**, Erwin W. Mueller Professor and Bascom Professor of Surface Science, Department of Materials Science and Engineering, University of Wisconsin–Madison; **C. Kumar N. Patel**, president and CEO, Pranalytica Inc.; **David A. Thompson**, retired, IBM Almaden Research Center; **Andrew M. Weiner**, Scifres Distinguished Professor, School of Electrical and Computer Engineering, Purdue University; **David A. Weitz**, professor of physics and applied physics, Department of Physics and SEAS, Harvard University; and **H. Kumar Wickramasinghe**, professor of EECS, biomedical engineering, and Henry Samueli Endowed Chair, Henry Samueli School of Engineering, University of California, Irvine. Paper, $34.00.

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