Spring 2015

FRONTIERS OF ENGINEERING

# The BRIDGE

LINKING ENGINEERING AND SOCIETY

**Progress in Self-Driving Vehicles**
*Chris Urmson*

**Personalized Medical Robots**
*Allison M. Okamura and Tania K. Morimoto*

**Electrochemical Prozac: Relieving Battery Anxiety through Life and Safety Research**
*Alvaro Masias*

**Lithium Ion Batteries and Their Manufacturing Challenges**
*Claus Daniel*

**The History of Heart Valves: An Industry Perspective**
*Erin M. Spinner*

**Biomaterials for Treating Myocardial Infarctions**
*Jason A. Burdick and Shauna M. Dorsey*

**Regulatory Perspectives on Technologies for the Heart**
*Tina M. Morrison*

**Microbial Ecology of Hydraulic Fracturing**
*Kelvin B. Gregory*

NATIONAL ACADEMY OF ENGINEERING
OF THE NATIONAL ACADEMIES

*The mission of the National Academy of Engineering is to advance the well-being of the nation by promoting a vibrant engineering profession and by marshalling the expertise and insights of eminent engineers to provide independent advice to the federal government on matters involving engineering and technology.*

The
BRIDGE

## NATIONAL ACADEMY OF ENGINEERING



*Editor in Chief*: Ronald M. Latanision

*Managing Editor*: Cameron H. Fletcher

*Production Assistant*: Penelope Gibbs

*The Bridge* (ISSN 0737-6278) is published quarterly by the National Academy of Engineering, 2101 Constitution Avenue NW, Washington, DC 20418. Periodicals postage paid at Washington, DC.

Vol. 45, No. 1, Spring 2015

Postmaster: Send address changes to *The Bridge*, 2101 Constitution Avenue NW, Washington, DC 20418.

Papers are presented in *The Bridge* on the basis of general interest and timeliness. They reflect the views of the authors and not necessarily the position of the National Academy of Engineering.

*The Bridge* is printed on recycled paper. ♻



A complete copy of *The Bridge* is available in PDF format at *www.nae.edu/TheBridge*. Some of the articles in this issue are also available as HTML documents and may contain links to related sources of information, multimedia files, or other content.

The
Volume 45, Number 1 • Spring 2015
BRIDGE
LINKING ENGINEERING AND SOCIETY

## Editor's Note

3 **From the Frontiers of Engineering and Beyond**
*Kristi S. Anseth*

## Features

5 **Progress in Self-Driving Vehicles**
*Chris Urmson*
Self-driving vehicles offer the promise of reducing accidents, enabling people who cannot drive to get around, and reducing congestion.

9 **Personalized Medical Robots**
*Allison M. Okamura and Tania K. Morimoto*
Robotic devices can achieve the most minimally invasive trajectory possible, thus increasing accuracy, minimizing trauma, and decreasing recovery time and chance of infection.

13 **Electrochemical Prozac: Relieving Battery Anxiety through Life and Safety Research**
*Alvaro Masias*
The success of long-term vehicle electrification efforts will depend heavily on the performance of their batteries.

21 **Lithium Ion Batteries and Their Manufacturing Challenges**
*Claus Daniel*
Research is being conducted to address materials, manufacturing, and cost challenges that hamper broader use of lithium ion batteries.

25 **The History of Heart Valves: An Industry Perspective**
*Erin M. Spinner*
New materials, technologies, and methods are enabling the transcatheter replacement and repair of diseased heart valves.

31 **Biomaterials for Treating Myocardial Infarctions**
*Jason A. Burdick and Shauna M. Dorsey*
Injectable biomaterials are being developed as a minimally invasive approach to decrease damage after a heart attack.

37 **Regulatory Perspectives on Technologies for the Heart**
*Tina M. Morrison*
Manufacturers of innovative medical technologies for the heart can leverage different tools and techniques to meet regulatory requirements and get their devices to the market.

*(continued on next page)*

43 **Microbial Ecology of Hydraulic Fracturing**
*Kelvin B. Gregory*
Storage and transportation of wastewater from unconventional oil and gas production create challenges in microbial control of the water.

49 **An Interview with . . .**
Henry Petroski

## NAE News and Notes

56 Class of 2015 Elected
60 NAE Members Receive One National Medal of Science and Four National Medals of Technology and Innovation
62 NAE Newsmakers
64 2014 EU-US Frontiers of Engineering Hosted by Boeing in Seattle
67 Message from NAE Vice President Corale Brierley
70 National Academy of Engineering 2014 Donor Recognition
84 Mirzayan Fellows Join Program Office
84 In Memoriam
86 Calendar of Meetings and Events

86 **Publications of Interest**

# Editor's Note

Kristi S. Anseth (NAE) is Distinguished Professor, Tisone Professor, and HHMI investigator in the Department of Chemical and Biological Engineering at the University of Colorado Boulder.

## From the Frontiers of Engineering and Beyond

The twentieth US Frontiers of Engineering (FOE) Symposium was hosted at the Beckman Center in Irvine, California, September 11–13, 2014. This annual program brings together 100 or so exceptionally talented young engineers, ages 30–45, representing the diversity of the engineering research community. The unique characteristic of the symposium is the opportunity to network with researchers working in academia, industry, and government and spanning engineering disciplines, and to learn about cutting-edge research on topics that stretch minds and thinking outside of one's own expertise. I have been privileged to chair this meeting for the past three years, and each event has been distinctively memorable. I hope you will consider nominating your eligible colleagues for next year's symposium, which will be organized by the new FOE chair, Professor **Robert Braun**, from the Georgia Institute of Technology.

The 2014 meeting began with a special welcome from NAE President **Dan Mote**, who shared a brief history of the NAE and upcoming events to celebrate its 50th anniversary. We were moved by a preview of some of the Engineering for You (E4U) video submissions (www.nae.edu/e4u/#contestMenu) and the takeaway message that "Engineering Is Amazing!"

We then commenced with the scientific program, which was organized into four sessions with the following themes: co-robotics, battery anxiety, technologies for the heart, and shale gas and oil. Eight papers based on this year's presentations are included in this issue of the *Bridge*.

The session on co-robotics was organized by Brian Gerkey of the Open Source Robotics Foundation and Carmel Majidi of Carnegie Mellon University. Speakers described how recent advances in robotics technology have enabled safer interactions with humans and are allowing robots to enter workplaces, hospitals, and homes. We learned about the frontiers in self-driving cars, robots in the manufacturing environment, minimally invasive surgical robots, and biologically inspired mobile robots. This issue features the papers of two speakers from this session, Chris Urmson of Google and Allison Okamura of Stanford.

The second session, chaired by Dan Steingart of Princeton University and Jeff Sakamoto of the University of Michigan, was titled "battery anxiety," which was intended to capture the efforts and challenges in transitioning to an electrical energy economy. The session highlighted efforts to meet future energy storage needs through both fundamental and applied materials research. The speakers covered topics about battery life and safety issues, linking fundamental materials characterization to manufacturing issues and grid storage. Alvaro Masias of Ford explains "why we need batteries," but places this in the context of reducing concerns about predictions of their lifetime and safety. Claus Daniel of Oak Ridge complements this discussion with a review of current and future chemistries for batteries as well as challenges in transitioning between materials discovery and energy storage technologies.

The theme of the third session, organized by Karen Christman of the University of California at San Diego and Ashley Peterson of Medtronic Endovascular Therapies, was technologies for the heart. The session introduced the audience to the basic functions of the heart to provide an appreciation for the complexities of engineering devices to interface with a living tissue. Erin Spinner of Edwards Lifesciences set the stage with a chronology of advances in devices to treat heart valve disease. Jason Burdick of the University of Pennsylvania then describes bench to bedside efforts in biomaterial design to treat the heart after an infarction. The session's closing talk, authored by Tina Morrison of the US Food and Drug Administration, explained the guidelines and constraints of FDA regulation for those in the business of engineering products for placement in the human body.

The final session, chaired by Billy Bardin of the Dow Chemical Company and Christopher Jones of the Georgia Institute of Technology, looked at the boom in domestic production of gas and oil from shale resources, facilitated by the development and implementation of hydraulic fracturing. Speakers provided an overview of the logistical and infrastructure challenges of transporting these resources, introduced some environmental questions and challenges, and discussed the use of shale gas for chemical production. In this issue Kelvin Gregory of Carnegie Mellon University reviews some of the water resource aspects related to hydraulic fracturing, specifically its impact on microbial communities.[1]

Beyond the outstanding presentations, the FOE schedule was designed to provide ample time for lively Q&A sessions, breakout discussions, and other activities to encourage conversation and networking. Another highlight of this year's program was the dinner speaker, Dr. **Arun Majumdar**, President Obama's selection for founding director of the Advanced Research Projects Agency–Energy (ARPA-E) and professor of mechanical engineering and materials science and engineering at the University of California at Berkeley. Dr. Majumdar gave a provocative talk on the notion of "what is impact?" with some historical context about the use of sources of nitrogen to tackle the problem of growing enough food for the world's population and the impact of the Haber-Bosch process. He challenged the audience to think about the most important problems facing society today and how one might rethink traditional measures of research success to include impact in developing solutions to global challenges in sustainability, energy, and environment.

I would like to conclude by emphasizing what a distinct pleasure it has been to serve as chair of the Organizing Committee for the US FOE Symposium for the past three years. I extend my heartfelt gratitude to Janet Hunziker, NAE senior program officer, and Vanessa Lester, program associate, who work tirelessly to ensure the success of this program. I feel so very fortunate to have been part of the FOE team for this brief period, and Janet and Vanessa deserve many rounds of thank you's from me, the session organizers, speakers, and meeting attendees for their extraordinary efforts. Finally, I would like to recognize the generous sponsors of the 2014 symposium: The Grainger Foundation, National Science Foundation, Defense Advanced Research Projects Agency, Air Force Office of Scientific Research, DOD-ASDR&E Research Directorate–STEM Development Office, Microsoft Research, Boeing, Cummins Inc., and individual donors.

[1] Editor's note: The topic of shale gas was addressed in the summer 2014 issue of the *Bridge*.

*Self-driving vehicles offer the promise of reducing accidents, enabling people who cannot drive to get around, and reducing congestion.*

# Progress in Self-Driving Vehicles

Chris Urmson is head of engineering for Google's Self-Driving Car Project.

Chris Urmson

Automated driving has experienced a research renaissance in the past decade as investigators have been motivated by organized competitions to increase safety and mobility. Key advances that have shaped the field during this period have been in the application of machine learning, large-scale mapping, improved LIDAR (*light detection and ranging* remote sensing technology) and radar sensing capability, and, more recently, a deeper understanding of the human factors that will influence the form in which this technology comes to market.

## Why Self-Driving Vehicles?

Traffic accidents are the leading cause of death for individuals aged 4 to 34 in the United States (Hoyert and Xu 2012). More than 30,000 people are killed each year on the road, and over 90 percent of these accidents are due to human error. Furthermore, the ability to move in, through, and around cities is decreasing as more and more drivers, preferring individual mobility, flood roadways. Yet the importance of personal mobility in the United States is such that when individuals lose the privilege of driving, and the social connections it enables, their life expectancy drops precipitously (Edwards et al. 2009). And in developing cities the rise in traffic deaths and significant pollution is further evidence of the tragedy of the commons.

Self-driving vehicles offer the promise of addressing all of these challenges: they should dramatically reduce accidents, enable people who cannot drive to get around, and, when deployed as part of an efficient shared vehicle fleet, reduce congestion.

FIGURE 1 The top three finishers in the 2005 DARPA Grand Challenge: Stanley, entered by Stanford University (left), and H1ghlander (center) and Sandstorm (right), both entered by Carnegie Mellon University.

## A Deep History

As early as the 1939 World's Fair, General Motors showed a concept of the automated roadway of the future. In 1950 its research and development department introduced the Firebird II concept car, capable of following buried cables that emitted a radiofrequency signal. During the 1980s and '90s the introduction of the microcomputer enabled practical, online computation on a mobile platform. Ernst Dickmanns was a pioneer in this space, introducing early versions of foveated stereovision systems (Dickmanns and Wünsche 2007).

Soon machine learning began to be applied to the problem. RALPH (a rapidly adapting lateral position handler; e.g., Thorpe and Kanade 1990) was one of the earliest applications of machine learning (neural networks in this case) to automated driving. By 1997 the combination of RALPH with a nascent forward-looking radar system enabled vehicles to drive thousands of miles. Elements of this technology have found their way into lane keeping assist systems, forward collision mitigation braking, and adaptive cruise control systems.

## DARPA's Grand Challenges

Much of the on-road automated driving work faded after the successful 1997 National Automated Highway Systems Consortium demonstration. The technology worked reasonably well, but automated driving research funding turned toward the military while the automotive industry slowly commercialized driver assistance systems.

In 2003 the driving research community was reenergized by the announcement of the DARPA Grand Challenges (http://grandchallenge.org/). The Floyd D. Spence National Defense Authorization Act for fiscal year 2001 called for one third of all US military ground vehicles to be unmanned by 2015. In a 2002 report the National Research Council indicated that this goal would not be achievable and that the Department of Defense should pursue other strategies (NRC 2002). Thus DARPA's Grand and Urban Challenges were born.

The initial Grand Challenges were off-road races across the desert, with the notional goal of having autonomous vehicles drive from Los Angeles to Las Vegas without remote assistance. In 2004 the challengers went only 7 miles of the 150-mile course (Urmson et al. 2004). The following year, several vehicles completed the competition (Figure 1), which was won by a team from Stanford (Thrun et al. 2006).

The vehicles featured several notable technical innovations. All of the competitors were given a rough map of the route, but several of the successful teams augmented the map data with information from other publicly available sources. The notion of fusing such information with onboard sensing data was novel at the time (Urmson et al. 2006). The approach was enabled by newly available access to high-resolution aerial imagery, and gave the vehicles a degree of foreknowledge of the terrain that resulted in better and safer driving.

The Stanford team used machine learning techniques extensively. For example, its vehicle used machine learning to bolster its visual system with LIDAR sensors, enabling it to drive faster than was possible with LIDAR alone. The vehicle was able to detect rough terrain and slow appropriately using a learned model of "bumpiness." The team's success in the challenge helped reinforce machine learning's value in the field of autonomous driving.

## The Urban Challenge

While the Grand Challenge was indeed a grand challenge, the vehicles operated in a world devoid of other moving vehicles: when Stanley, the Stanford vehicle, passed H1ghlander, the Carnegie Mellon vehicle, to claim the victory, H1ghlander was paused and Stanley passed an inert vehicle.

The Urban Challenge was thus the next evolution of the DARPA competition, in which the vehicles now had not only to complete the challenge with moving vehicles but also to obey a subset of driving rules that human drivers take for granted (e.g., stay in the lane, follow precedence rules at intersections, avoid other vehicles). The competition, staged in 2007, required vehicles to drive 60 miles around a decommissioned Air Force base in Victorville, California. Six vehicles finished the competition, with teams from Carnegie Mellon, Stanford, and Virginia Tech in the top three positions (Buehler et al. 2009).

Key technical advances came in the form of high-density LIDAR and further demonstration of the value of high-density maps. Single-plane LIDAR sensors were used in the original Grand Challenge, sometimes actuated to sweep volumes but generally carefully calibrated to sweep scan lines through the environment as the vehicle moved. The Urban Challenge introduced the concept of high-density LIDARs through a sensor developed by Velodyne. The new sensor had a spinning head that swept a set of 64 LIDAR emitters through space, generating over 1 million range measurements per second with relatively high angular resolution. This style of sensor enabled a new level of precision modelling that had until then been difficult, if not impossible, to achieve in real time.

The value of digital maps came to the forefront during the Urban Challenge. Using the maps, vehicles were able to anticipate the likely trajectory of other vehicles and focus their attention in appropriate directions at intersections. They were also able to use their limited computation more efficiently.

### Post-Challenge Progress

In the seven years since the Urban Challenge, industry has taken up the gauntlet of advancing self-driving technology. In 2009 Google started a program to develop self-driving vehicles and since then its vehicles have driven more than 700,000 miles autonomously on public roads.

The technology being developed by Google builds on many of the themes developed during the DARPA challenges. The vehicles use high-resolution maps (now being developed at city scale) to help guide the onboard system's perception and planning behaviors as well as a combination of LIDAR, camera, and radar sensors to provide a partially redundant and multispectral model of the environment. The onboard software system leverages hundreds of thousands of miles of driving data and machine learning techniques to predict the behavior of other road users.

In parallel with Google's efforts, the automotive industry is broadly engaged in the development of advanced driver assistance systems, with the major car companies and their suppliers developing varying degrees of automated driving. The largest difference between the approaches of the classical automotive companies and Google is the degree to which the driver is engaged. Google is developing vehicles to be fully self-driving, requiring a rider only to tell the vehicle where to go (Figure 2), whereas the automotive companies are primarily focused on delivering advanced driver assistance systems that require the driver to remain in the steering loop. The latter approach requires a smaller incremental technical step, but is challenged

FIGURE 2 Google's prototype fully self-driving vehicle.

by problems of driver attentiveness and skill atrophy (Llaneras et al. 2013).

In the coming years advanced driver assistance systems and self-driving vehicles will become commonplace, delivering on the promise of making roads safer and more convenient for all.

## References

Buehler M, Iagnemma K, Singh S, eds. 2009. The DARPA Urban Challenge: Autonomous vehicles in city traffic. Spring Tracts in Advanced Robotics, vol. 56. London: Springer.

Dickmanns ED, Wünsche HJ. 2007. Dynamic vision for perception and control of motion. London: Springer.

Edwards JD, Perkins M, Ross LA, Reynolds SL. 2009. Driving status and three-year mortality among community-dwelling older adults. Journals of Gerontology Series A: Biological Sciences and Medical Sciences 64A(2):300–305.

Hoyert DL, Xu J. 2012. Deaths: Preliminary data for 2011. National Vital Statistics Reports 61(6):1–51.

Llaneras RE, Salinger J, Green CA. 2013. Human factors issues associated with limited ability autonomous driving systems: Drivers' allocation of visual attention to the forward roadway. Proceedings of the 7th International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design, pp. 92–98.

NRC [National Research Council]. 2002. Technology Development for Army Unmanned Ground Vehicles. Washington: National Academies Press.

Thorpe C, Kanade T. 1990. Vision and Navigation. Dordrecht: Kluwer Academic Publishers.

Thrun S, Montemerlo M, Dahlkamp H, Stavens D, Aron A, Diebel J, and 24 others. 2006. Stanley: The robot that won the DARPA Grand Challenge. Journal of Field Robotics 23(9):661–692.

Urmson C, Anhalt J, Clark M, Galatali T, Gonzalez JP, Gowdy J, and 10 others. 2004. High speed navigation of unrehearsed terrain: Red Team technology for Grand Challenge 2004. Technical Report CMU-RI-04-37. Robotics Institute, Carnegie Mellon University, Pittsburgh.

Urmson C, Ragusa C, Ray D, Anhalt J, Bartz D, Galatali T, and 16 others. 2006. A robust approach to high-speed navigation for unrehearsed desert terrain. Journal of Field Robotics 23(8):467–508.

*Robotic devices can achieve the most minimally invasive trajectory possible, thus increasing accuracy, minimizing trauma, and decreasing recovery time and chance of infection.*

# Personalized Medical Robots

Allison M. Okamura

Tania K. Morimoto

Allison M. Okamura and
Tania K. Morimoto

Many medical interventions today are qualitatively and quantitatively limited by human physical and cognitive capabilities. Robot-assisted intervention techniques can extend humans' ability to perform surgery more accurately and less invasively using novel physical designs and computer control. Hundreds of thousands of surgical procedures are now done annually using robots, typically teleoperated by human surgeons. Commercial surgical robots such as the da Vinci Surgical System (DiMaio et al. 2011) are designed as general tools that can be used for a variety of procedures and patient populations. But because of their limited dexterity, high cost, and large footprint in the operating room, there are many scenarios in which current clinical robots cannot be used to perform minimally invasive medical procedures (Herron and Marohn 2008; Taylor and Stoianovici 2003). The next generation of medical robots will be much more personalized—capable of being rapidly designed, manufactured, and controlled for a specific patient and procedure.

## Design of Personalized Medical Robots

Each patient presents a design opportunity. A path from a feasible entry point on the surface of the body to the target, such as a cancerous tumor or kidney

Allison M. Okamura is an associate professor and Tania K. Morimoto is a graduate student in the Department of Mechanical Engineering at Stanford University.

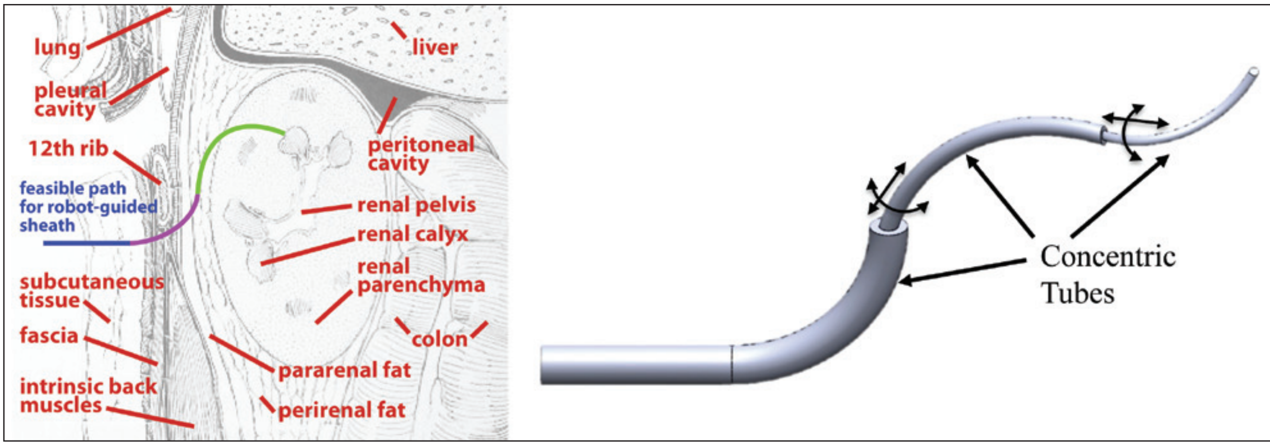



FIGURE 1 Personalized medical robot design uses knowledge of patient anatomy (left) to select the number, shape, and length of robotic elements (right) to reach a target in the safest, most minimally invasive fashion possible. Adapted from Morimoto et al. (2013).

stone, can be planned based on patient-specific anatomy and mechanical models of tissue acquired via new elastographic imaging techniques. Based on this path, a unique robotic steerable needle or catheter design will achieve the most minimally invasive trajectory possible, thus increasing accuracy, minimizing trauma, and ideally decreasing recovery time and chance of infection. This capacity is particularly useful in addressing the needs of specialized patient groups, including children and people with rare diseases, who may otherwise not receive the optimal treatment.

In many procedures, the path of least resistance from a feasible entry point on the surface of the body to a target for treatment has multiple curved segments, so a snakelike device with the ability to change its shape along its length is ideal. To avoid the "curse of dimensionality" (the challenge of modeling and controlling a system with hundreds of individual degrees of freedom), a useful robot design should require only a few input degrees of freedom, yet have the ability to achieve a large variety of physical configurations. Steerable needles (Reed et al. 2011) have this property, but require relatively large reaction forces from tissue and cannot work in free space.

One of the most promising approaches is the *concentric tube robot* (also known as the *active cannula*), which consists of nested hollow, precurved, superelastic tubes (Figure 1). As the curved tubes are inserted and rotated with respect to each other, they interact such that their common axis conforms to some combined curvature, causing the overall shape of the robot to change. Because concentric tube robots derive bending actuation from the elastic energy stored in the backbone, they do not require reaction forces to bend and can be used in free space. The concept for the active cannula was simultaneously developed in 2006 (Sears and Dupont 2006; Webster et al. 2006), and recent work has provided a comprehensive analysis of concentric tube robot design and kinematics (Gilbert and Webster 2013; Lock and Dupont 2011; Rucker et al. 2010; Webster et al. 2008).

One example of concentric tube robot design is given in the context of accessing hard-to-reach upper-pole kidney stones in pediatric patients (Morimoto et al. 2013). Because of their smaller body surface area compared to adults, as well as the proximity of the upper kidney to the diaphragm and the pleura, traditional straight needle- and catheter-based approaches can be dangerous. To eliminate these risks, the ideal path would begin below the 12th rib, snake up through the renal pelvis, and curve toward the upper pole of the kidney. The exact dimensions for curvatures and segment lengths of the tubes can be gauged from patient-specific CT scans. Based on kinematic models (Dupont et al. 2010; Sears and Dupont 2007; Webster et al. 2008, 2009), sets of tubes can be identified that follow the desired path through patient tissue (Figure 1).

## Manufacturing of Personalized Medical Robots

A combination of modular robot architecture and novel manufacturing techniques is beginning to enable fast manufacturing and assembly of robotic manipulators that can achieve a variety of design objectives. Primarily these robots will be long, thin, flexible devices whose actuators remain outside the body and whose components that enter the body are sterile and disposable—they are small, inexpensive, and do not need to be overdesigned for repeated use. The nondisposable base of the robot can consist of modular units.

In the case of a modular concentric tube robot design, a single module includes two motors that allow a tube to be both inserted and rotated with respect to the tubes around it (Figure 2). The outermost tube to be inserted is clamped in the modular unit at the end of the base closest to the patient, while the subsequent tubes (with increasingly smaller diameters) are axially aligned in units further behind. Units can be added or removed based on the number of tubes needed for the specific procedure and patient.

The disposable components of the robot can be either specifically designed for each patient or chosen from a set that has been previously designed and optimized for a particular population of patients (e.g., children). A patient-specific design requires the manufacture of numerous disposable components. In one method for active cannula manufacturing, superelastic (e.g., Nitinol) tubes are heat treated to take on the desired shapes.

Recent work has taken advantage of advances in 3D printing to quickly and cheaply produce patient-specific devices (Figure 2). The use of 3D printing is becoming more widespread in the medical field for anatomy visualization to improve surgical planning (Dankowski et al. 2014; Schwaiger et al. 2012) and for the production of customized implants for patients with special requirements and size constraints (Abdel-Sayed and von Segesser 2011). 3D printing is also increasingly used for manufacturing medical robots, from rehabilitation devices to minimally invasive surgical robots (Roppenecker et al. 2013). The benefits of 3D printing include speed, the use of multiple materials in a single part, and the ability to embed sensors in a mechanical structure.

### Control of Personalized Medical Robots

Surgical robots that go deep into the body require a combination of low-level autonomous control and high-level human control. Human teleoperation directs the robot tip motions and treatments, while the underlying control system achieves the necessary robot configuration to minimize invasiveness. Seamless integration of preoperative plans and real-time medical imaging provide effective feedback to achieve the desired clinical outcomes. Examples of control systems that involve both low-level autonomous control and high-level human control include teleoperators that combine haptic (force feedback) guidance for steerable needles (Majewicz and Okamura 2013) and operator tip control for active cannulas (Burgner et al. 2011).

### Conclusion

The next generation of medical robots will be personalized to enable treatment using devices optimized for a particular patient's body and malady. Advances in medical imaging, path planning, design, manufacturing, control, and human-machine interaction all contribute to this goal.

### References

Abdel-Sayed P, von Segesser LK. 2011. Rapid prototyping for training purposes in cardiovascular surgery. In: Advanced Applications of Rapid Prototyping Technology in Modern Engineering, ed. Hoque ME, Chapter 4. Rijeka, Croatia: InTech.

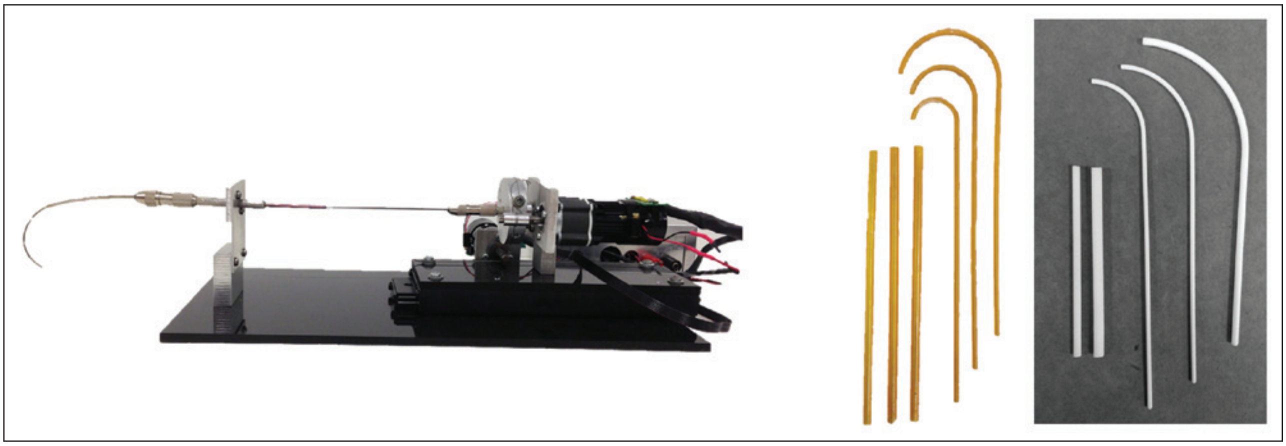


FIGURE 2 (Left) Active cannula-driving robot module. (Right) Example sets of 3D-printed tubes that can be used to construct an active cannula system.

Burgner J, Swaney PJ, Rucker DC, Gilbert HB, Nill ST, Russell PT, Weaver KD, Webster RJ. 2011. A bimanual teleoperated system for endonasal skull base surgery. Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, San Francisco, September 25–30, pp. 2517–2523.

Dankowski R, Baszko A, Sutherland M, Firek L, Kałmucki P, Wróblewska K, Szyszka A, Groothuis A, Siminiak T. 2014. 3D heart model printing for preparation of percutaneous structural interventions: Description of the technology and case report. Kardiologia Polska 72(6):546–551.

DiMaio S, Hanuschik M, Kreaden U. 2011. The *da Vinci* surgical system. In: Surgical Robotics: Systems Applications and Visions, Chapter 9. New York: Springer Science and Business Media.

Dupont PE, Lock J, Itkowitz B, Butler E. 2010. Design and control of concentric-tube robots. IEEE Transactions on Robotics 26(2):209–225.

Gilbert HB, Webster RJ. 2013. Can concentric-tube robots follow the leader? Proceedings of the 2013 IEEE International Conference on Robotics and Automation, Karlsruhe, Germany, May 6–10, pp. 4866–4872.

Herron DM, Marohn M. 2008. A consensus document on robotic surgery. Surgical Endoscopy 22:313–325.

Lock J, Dupont PE. 2011. Friction modeling in concentric-tube robots. Proceedings of the 2011 IEEE International Conference on Robotics and Automation, China, pp. 1139–1146.

Majewicz A, Okamura AM. 2013. Cartesian and joint space teleoperation for nonholonomic steerable needles. Proceedings of the IEEE World Haptics Conference, South Korea, pp. 395–400.

Morimoto TK, Hsieh MH, Okamura AM. 2013. Robot-guided sheaths (RoGS) for percutaneous access to the pediatric kidney: Patient-specific design and preliminary results. Proceedings of the 2013 ASME Dynamic Systems and Control Conference, Palo Alto, October 21–23; doi: 10.1115/DSCC2013-3917.

Reed KB, Majewicz A, Kallem V, Alterovitz A, Goldberg K, Cowan NJ, Okamura AM. 2011. Robot-assisted needle steering. Robotics and Automation Magazine 18:35–46.

Roppenecker DB, Pfaff A, Coy JA, Leuth TC. 2013. Multi-arm snake-like robot kinematics. Proceedings of the 2013 IEEE/RSJ International Conference on Intelligent Robotics and Systems, Japan, pp. 5040–5045.

Rucker DC, Jones BA, Webster RJ. 2010. A geometrically exact model for externally loaded concentric-tube continuum robots. IEEE Transactions on Robotics 26(5):769–780.

Schwaiger J, Kagerer M, Traeger M, Gillen S, Dobritz M, Kleeff J, Feussner H, Lueth TC. 2012. Manufacturing of patient-specific pancreas models for surgical resections. Proceedings of the 2012 IEEE International Conference on Robotics and Biomimetics, China, pp. 991–998.

Sears P, Dupont PE. 2006. A steerable needle technology using curved concentric tubes. Proceedings of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, China, pp. 2850–2856.

Sears P, Dupont PE. 2007. Inverse kinematics of concentric-tube steerable needles. Proceedings of the 2007 IEEE International Conference on Robotics and Automation, Italy, pp. 1887–1892.

Taylor RH, Stoianovici D. 2003. Medical robotics in computer-integrated surgery. IEEE Transactions on Robotics and Automation 19(5):765–781.

Webster RJ, Okamura AM, Cowan NJ. 2006. Toward active cannulas: Miniature snake-like surgical robots. Proceedings of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, China, pp. 2857–2863.

Webster RJ, Romano JM, Cowan NJ. 2008. Kinematics and calibration of active cannulas. Proceedings of the 2008 IEEE International Conference on Robotics and Automation, USA, pp. 3888–3895.

Webster R, Romano J, Cowan N. 2009. Mechanics of precurved-tube continuum robots. IEEE Transactions on Robotics 25(1):67–78.

*The success of long-term vehicle electrification efforts will depend heavily on the performance of their batteries.*

# Electrochemical Prozac

## Relieving Battery Anxiety through Life and Safety Research

Alvaro Masias is a research engineer in the Energy Storage Research & Strategy Department at Ford Motor Company.

Alvaro Masias

Global interest in electrified vehicles is sparked by both environmental concerns and, in practical terms, the relatively recent application of lithium ion battery technology to automotive applications. Mass adoption of automotive batteries will depend on performance improvements, so methods to optimize the prediction and design of this technology for endurance and safety are an area of active research. New analytical test tools and methods are described in this article, and their refinement and adoption will enhance the ability of lithium ion technology to supplant liquid hydrocarbon fuels in the transportation sector and thus positively contribute to the global environment.

### Introduction

The governments of the United States, European Union, China, and Japan, among others, have announced increasingly strict fuel economy regulations. Thus although the fossil fuel–powered automobile has been the subject of continuous engineering improvement for over 100 years (Ford 1988), electrified automobiles are a key component of virtually all automakers' current and future product portfolios, and lithium ion batteries are enabling a new generation of electrified vehicles to be commercialized by global automakers.

In this article I explain battery performance requirements for the broad range of electrified vehicles, together with new tools to improve the identification and prediction of failure mechanisms. Safety testing and the results of recent research in this area are also presented.

By addressing the sources of uncertainty in battery failure mechanisms, whether performance (i.e., precise measurement of voltage, current, and time) or safety (i.e., reaction to various types of mechanical and electrical abuse) related, researchers will enable significant improvements in future generations of battery-powered vehicles.

## Transportation Battery Needs

Electrified vehicle designs can be classified by their levels of electrification. In order of increasing power and energy demands, common electrified vehicle features include stop-start (maintaining normal vehicle functions at a stop while allowing the engine to turn off), regenerative braking (converting the kinetic energy of motion into stored electrical energy using the electric machines to supplement friction braking), motor assist, and electric vehicle (EV) drive (EVs run solely on electricity). The ability of hybrid electric vehicles (HEVs), which can convert liquid fuel energy into either mechanical or electrical energy, to perform these functions allows for differentiation between stop-start, mild (<20 kW), strong (>20 kW), and plug-in electric hybrids (PHEVs), which may consume some fossil fuel.

Until recently the performance and maturity of various battery chemistries determined their EV type suitability and commercialization. Now the recent maturation of lithium ion technology is driving a migration away from nickel metal hydride batteries for most HEV and EV applications. But low-temperature, cost, and life challenges prevent lithium ion technology from supplanting lead acid chemistries in the stop-start market.

The various EV types, with their different array of electrified features, place very different power, energy, and cycle life demands on their batteries. For example, a common EV design features more than 80 kW of power and 24 kWh of energy. Cycle life is strongly affected by the extent of the battery capacity used in each cycle. Likewise, designing for high energy has a direct impact on the available power delivery as a tradeoff.

Designing a vehicle battery involves balancing competing performance figures, including energy and power. As a result, several automotive industry and government organizations—the US Advanced Battery Consortium (USABC; information at www.uscar.org), the European Council for Automotive Research & Development (EUCAR; www.eucar.be), and the New Energy and Industrial Technology Development Organization (NEDO; www.nedo.go.jp)—have created EV performance targets for energy and power, designating targets for pack-level specific energy (energy by weight) and power (power by weight).

## Life Prediction

When determining the ability of a battery technology to meet future life requirements a high level of confidence is required. Consequently, qualifying a new technology for production can take several years of validation testing to meet the typical 10-year/150,000-mile vehicle life requirement. Testing first distinguishes between battery life decay mechanisms (use or calendar dependent) and then assesses the impacts of current levels (low, high) and temperature.

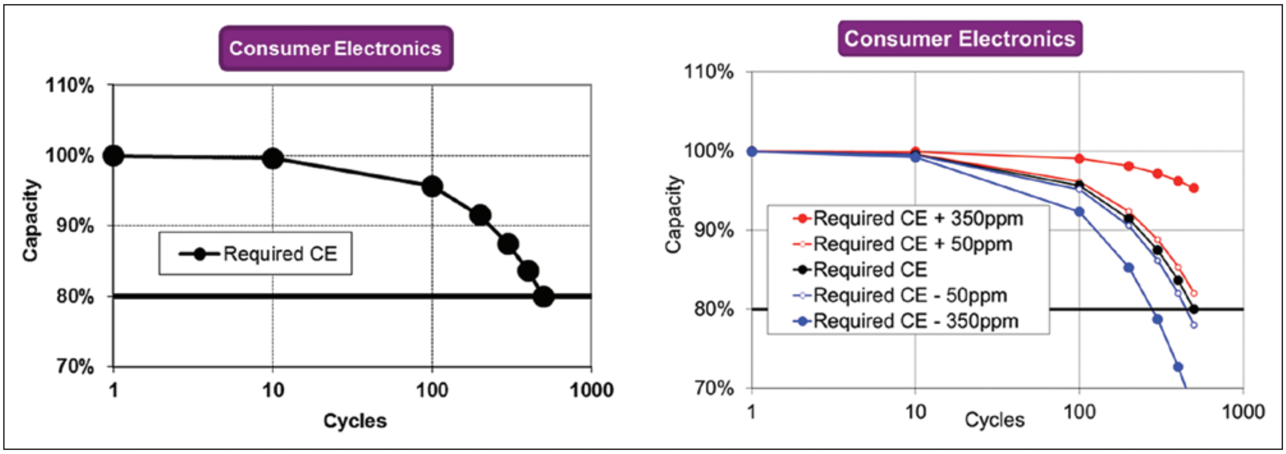



FIGURE 1 Coulombic efficiency (CE) required (L) and impact of tester imprecision (R).

*Battery Life Decay Mechanisms*

Battery life decay mechanisms can be categorized as *calendar* or *use dependent*. The former are tested in high-temperature protocols that take advantage of a battery's Arrhenius kinetic mechanisms, which lend themselves well to accelerated testing. Cycle life acceleration is more problematic, as its decay mechanism is more difficult to accelerate through established techniques. High-precision battery testing has recently been proposed as a method to accelerate the understanding of cycle life–based decay mechanisms (Smith et al. 2010). To make future life predictions, it is necessary that the precision of the test data be at least as good as the decay per cycle that is being predicted. By closely measuring current, voltage, and time during a battery test, it is possible to achieve the parts per million (ppm) level of measurement precision needed to predict hundreds and thousands of cycles into the future.

*Low Current*

To understand the impact of imprecise battery measurements, the example of coulombic efficiency (CE) in consumer electronic cell life requirements is shown in Figure 1. Coulombic efficiency is defined as the number of electrons that leave a battery divided by the number that entered. Based on this definition, a theoretically perfect battery would have a CE value of unity or 100 percent. If a cell delivered the exact amount of coulombic efficiency (99.954 percent or a deviation of 446 ppm from ideal) required to achieve 20 percent capacity decay in 500 cycles, the curve shown on the left in Figure 1 would be achieved. Existing battery testing equipment is subject to CE errors of nearly the same order of magnitude (350 ppm). To be relevant to EVs, where an order of magnitude improvement in cycles to 5,000 is desired, testers would need a corresponding error improvement to approximately 50 ppm. The righthand graph in Figure 1 shows that when the error is of about the same order of magnitude (350 ppm) as the allowable deviation (446 ppm), the predicted future capacity is uncertain. However when the tester error is reduced to 50 ppm, the predicted future capacity can be determined with more confidence.

Recognizing this opportunity for improvement, there has been growing interest in research on high-precision battery testing. Current academic systems have achieved 100 ppm error in terms of coulombic efficiency, with a goal of 10 ppm for future systems (Dahn et al. 2013; Smith et al. 2010). It should be noted that these systems are at low current rates (single-digit amps at the most). The impact of using a 100 ppm system on the imprecision of CE measurements is shown in Figure 2: the closer a battery's CE gets to unity (right side), the flatter its capacity decay cycle over time (left side).

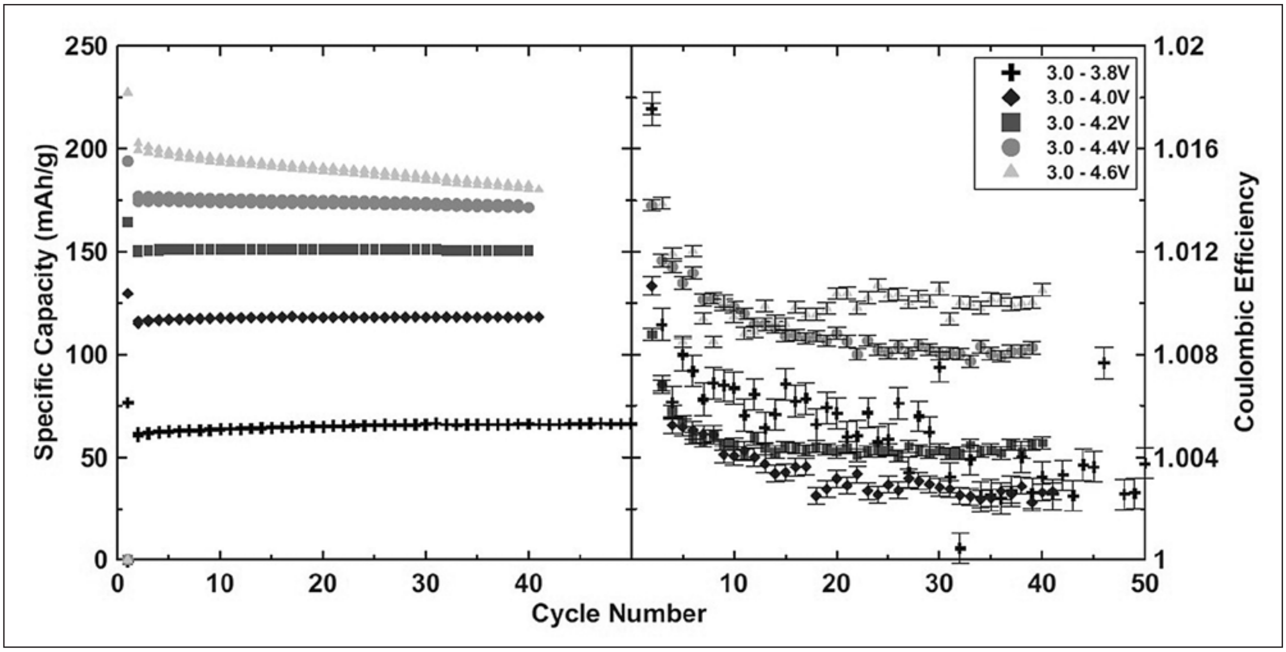



FIGURE 2 Capacity and high-precision Coulombic efficiency as a function of charge voltage. Reprinted with permission from Smith et al. (2010).

*High Current*

Automotive battery testing must demonstrate the capacity to support currents of at least several hundred amps, as would be typical of vehicle conditions. The range of power and corresponding current demands varies by vehicle type. Higher currents are achieved in power characterization patterns ranging from +300 to −120 amps (A) for the various electrified vehicle types. To address the challenges associated with improving the precision of capacity predictions at higher current and power levels, the Department of Energy's Advanced Research Projects Agency–Energy (ARPA-E) has awarded a research contract to Ford, Arbin Instruments, and Sandia National Labs to build a commercially viable 50 ppm 200A tester.[1] Project progress is described below.

**TABLE 1 US Federal Motor Vehicle Safety Standard 305 Requirements**

| | Section | Requirement |
|---|---|---|
| S5.1 | Electrolyte spillage from propulsion batteries | <5L spillage total, 0 into passenger cabin 30 minutes after barrier test |
| S5.2 | Electrical energy storage/ conversion device retention | Energy device shall remain attached to vehicle and out of passenger cabin |
| S5.3 | Electrical safety | Maintain isolation >100 ohm/volt with monitoring or >500 ohm/volt without monitoring |

Source: DOT (2008).

**TABLE 2 European Council for Automotive Research & Development (EUCAR) Battery Abuse Response Rating**

| Score | Title | Description |
|---|---|---|
| 0 | No effect | No effect. No loss of functionality. |
| 1 | Passive protection activated | Cell reversibly damaged. Repair of protection device needed. But no defect; no leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. |
| 2 | Defect/damage | Cell irreversibly damaged. Repair needed. But no leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. |
| 3 | Leakage ($\Delta$ mass < 50%) | Weight loss <50% of electrolyte weight (electrolyte = solvent + salt). No venting, fire, or flame; no rupture; no explosion. |
| 4 | Venting ($\Delta$ mass > 50%) | Weight loss of ≥50% of electrolyte weight (electrolyte = solvent + salt). No fire or flame; no rupture; no explosion. |
| 5 | Fire or flame | No rupture; no explosion (i.e., no flying parts). |
| 6 | Rupture | No explosion, but flying parts of the active mass. |
| 7 | Explosion | Explosion (i.e., disintegration of the cell). |

Source: Reprinted with permission from Doughty and Crafts (2005).

*Temperature*

Another significant challenge in testing at high currents is mitigation of the resulting temperature changes in the test cells and tester (e.g., shunts and amplifiers). For the test automotive cell, a thermal image can reveal temperature gradients. The order of magnitude of the gradient can vary widely depending on cell design and test pattern run, but its orientation remains the same. At the top of the cell, the connecting terminals serve as excellent thermal wicks (thanks to the highly thermally conductive metals used).

To explore the impact of high current–driven thermal gradients during high-precision testing, the Ford ARPA-E team has been developing thermal control strategies, one of which involves two thermoelectric (TE) heater/cooler assemblies surrounding a single cell. By coupling the intimate cooling capacity of the TEs with feedback (cell temperature) and feedforward (current delivery pattern and resulting cell-driven temperature change), it is possible to neutralize temperature fluctuations during the testing and study their effect (e.g., dV/dT) on precision.

[1] Information about the project, for which I am principal investigator, is available at ARPA-E, "Ultra-Precise Battery Tester," http://arpa-e.energy.gov/?q=slick-sheet-project/ultra-precise-battery-tester.

### Safety Prediction

Current and evolving government regulations and industry standards cover all aspects of automotive design. In the United States, these regulations take the form of the Federal Motor Vehicle Safety Standards (FMVSS), of which FMVSS 305 addresses electrified vehicles (Table 1).

As the technology and systems have evolved, FMVSS 305 has been revised numerous times since it was first issued in 2000. With the recent application of lithium ion batteries to automotive applications, the National Highway Traffic Safety Administration (NHTSA) has conducted research on the safety behavior of the technology. One of the NHTSA-sponsored research projects, conducted by Ford in collaboration with Ricardo, an international engineering and environmental consultancy, sought to develop recommendations for vehicle-level safety tests and performance metrics for NHTSA consideration. The project, completed in November 2014, included study of the behaviors of parts (e.g., cell strings, modules, and packs) to determine quantifiable vehicle-level recommended test procedures.

The most common way to describe the response of a lithium ion battery to abuse is to use the EUCAR rating system (Table 2), which assigns a score of 0 to 7 for a range of increasingly severe battery responses. For example, a score of 5 denotes a battery that experienced a fire or flame event.

The team performed a rigorous fault tree analysis (FTA) to consider all the possible lithium ion–specific faults a vehicle could experience and produced a ranked list of priority hazards, from which the top three—crush, overcharge, and short circuit—were selected for procedure development. A global survey of battery regulations and industry standards provided a baseline for the development of draft test procedures, which were then tested at three US locations. The sites evaluated string, module, and pack hardware built up with three types of lithium ion cells. The experimental testing and analysis allowed for significant test procedure refinement and confidence in battery responses.

Battery abuse tests generally fall into one of three categories: mechanical, thermal, and electrical. The following sections present the range of testing for each category and, where appropriate, the results and recommendations of Ford's research.

#### *Mechanical Abuse*

International battery safety mechanical test regulations and standards vary significantly (Table 3). The most common test combines mechanical shock and mechanical integrity testing, in which the battery is typically subjected to a mechanical crush event.

**TABLE 3 Mechanical safety test matrix**

| Test type | Industry standard | | | | | Government regulation | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Freedom Car | SAE J2929 | SAE J2464 | ISO 12405-1 | ISO 12405-3 | UN 38.3 | ECE R100 | Q/C-T 743 | KMVSS 1.48 |
| Mechanical integrity | ● | ● | ● | | ● | | ● | ● | |
| Mechanical shock | ● | ● | ● | ● | ● | ● | ● | | |
| Penetration | ● | | ● | | | | | ● | |
| Immersion | ● | ● | ● | | ● | | | | ● |
| Rollover | ● | | ● | | | | | | |
| Drop | ● | ● | ● | | ● | ● | | ● | ● |
| Vibration | | ● | | ● | ● | ● | ● | ● | |

Note: ECE = Economic Commission for Europe, ISO = International Organization for Standardization, KMVSS = Korea Motor Vehicle Safety Standards, Q/C-T = China Industry Standard, SAE = Society of Automotive Engineers, UN = United Nations.

Review of the large number of existing crush-related tests led to selection of the FreedomCar procedure as a starting point (INEEL 2003). The procedure was modified to stratify the battery response by breaking up the crush motion into 20 increments of 5 percent. By crushing in many small steps over approximately one hour, it was possible to determine the impact of a fault as it progressed.

All hardware was able to be crushed to more than 13 percent displacement without a EUCAR 5 (fire or flame) response. The broad plane of the cell had the smallest ranges of response, indicative of testing consistency. Designing a parts-level crush test for the other planes of the cell is nontrivial because of the tendency of hardware to move out of the plane of crush when not constrained in a vehicle. As a result, it was concluded that crush testing should be performed only at the vehicle level and in the same manner as current FMVSS crash tests. If a battery experiences mechanical damage during these tests, the extent of battery crush can be used to assess the result.

Improvements in computing power and modeling capabilities have revolutionized automotive design and in particular crush performance development. Research in this area should seek to couple experimental results with simulations in the hopes of supplanting the need for trial and error experimentation (Sahraei et al. 2014).

### *Thermal Abuse*

There is considerable variability in the use of thermal testing protocols (Table 4), with only two—the thermal shock and fire exposure tests—close to a consensus position among the regulatory and standards agencies.

Thermal shock testing typically involves exposing a battery pack to a cycle of warm and cold temperatures and then evaluating its performance, making it more of a durability evaluation procedure than an abuse failure investigation tool.

For fire exposure investigation, an ECE regulation (R34) that calls for a fire exposure test on plastic fuel tanks in vehicles has been referenced, and the test, adapted for battery abuse testing, incorporated in a new regulation (R100) (Figure 3). It involves first directly exposing a battery to a burning pool of liquid fuel (Phase B) and then indirectly through a screen of refractory bricks (Phase C) and evaluating the hardware response (Phase D).

**TABLE 4 Thermal safety test matrix**

| Test type | Industry standard | | | | | Government regulation | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Freedom Car | SAE J2929 | SAE J2464 | ISO 12405-1 | ISO 12405-3 | UN 38.3 | ECE R100 | Q/C-T 743 | KMVSS 1.48 |
| Thermal shock | ● | ● | ● | ● | ● | ● | ● | | |
| Fire exposure | ● | ● | ● | | ● | | ● | | ● |
| Thermal stability | ● | | | | | | | | |
| High-temperature storage | ● | | | | | | | ● | ● |
| Cycle without thermal control | ● | ● | ● | | ● | | ● | | |
| Humidity exposure | | ● | | ● | ● | | | | |
| Passive propagation | | | ● | | | | | | |

Note: ECE = Economic Commission for Europe, ISO = International Organization for Standardization, KMVSS = Korea Motor Vehicle Safety Standards, Q/C-T = China Industry Standard, SAE = Society of Automotive Engineers, UN = United Nations.

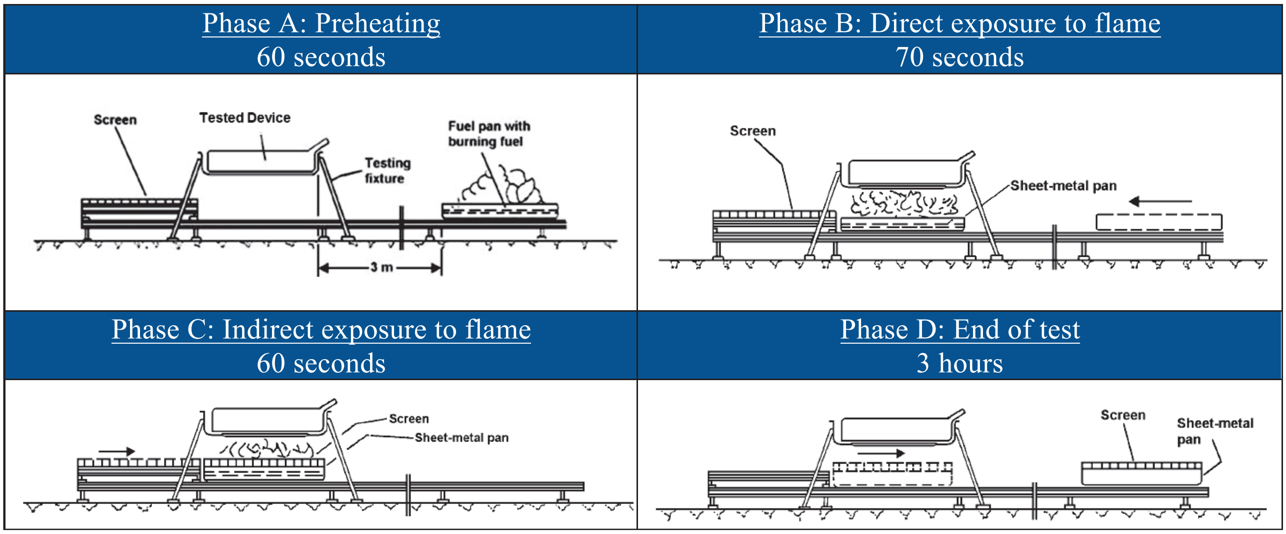



FIGURE 3 United Nations Economic Commission for Europe (UNECE) R100 fire exposure test. Reprinted with permission from UNECE (2013).

*Electrical Abuse*

The electrical subcategory of battery safety testing (Table 5) shows the greatest consistency of application: all the reviewed regulations and standards feature overcharge, short circuit, and overdischarge tests. There are minor differences in test details (e.g., in current, duration, or resistance), but the general procedures are similar.

The Ford team investigated battery responses to overcharge and found that attempts at discretizing the moment of battery response led to a start-stop approach to overcharge electrical energy delivery using twenty 5 percent state of charge intervals. No hardware had an event before it reached 134 percent overcharge. Thus, in the unlikely event that a vehicle allowed an overcharge to occur, the state of charge can be used to assess the test's outcome.

Short circuit abuse testing of batteries commonly uses shunts of specific resistances (e.g., 10mΩ), irrespective

**TABLE 5 Electrical safety test matrix**

| Test type | Industry standard | | | | | Government regulation | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Freedom Car | SAE J2929 | SAE J2464 | ISO 12405-1 | ISO 12405-3 | UN 38.3 | ECE R100 | Q/C-T 743 | KMVSS 1.48 |
| Overcharge | ● | ● | ● | ● | ● | ● | ● | ● | ● |
| Short circuit | ● | ● | ● | ● | ● | ● | ● | ● | ● |
| Over-discharge | ● | ● | ● | ● | ● | ● | ● | ● | ● |
| High-voltage exposure | | ● | | | | | | | |
| Partial short circuit | ● | | | | | | | | |
| Separator shutdown | | | ● | | | | | | |

Note: ECE = Economic Commission for Europe, ISO = International Organization for Standardization, KMVSS = Korea Motor Vehicle Safety Standards, Q/C-T = China Industry Standard, SAE = Society of Automotive Engineers, UN = United Nations.

of the test hardware details. This approach ignores the Ohm's law behavior of the short circuit reaction, which dictates that the severity of the short is dependent on the relative resistance of the hardware to the shunt. By exploring a range of relative resistance values it is possible to correlate test current and shunt resistance to the likely test outcome. Review of a vehicle battery's internal resistance and limits imposed by the pack's fusing is informative of the likely abuse response.

## Conclusion

The success of long-term vehicle electrification efforts will depend heavily on the performance of their batteries. Batteries appropriate for automotive applications have to pass extensive validation procedures to demonstrate durability, but there remain uncertainties—causes for anxiety—about battery life and safety. New testing tools are available to improve the prediction and identification of electrochemical failure mechanisms. Further research can enhance the utility and international consistency of these testing procedures to align developments and progress.

## Acknowledgments

This work was supported by the US Department of Transportation's National Highway Traffic Safety Administration (NHTSA) [DTNH22-11-C-00214] and the US Department of Energy's Advanced Research Projects Agency–Energy (ARPA-E) [DE-AR000267].

## References

Dahn JR, Trussler S, Dugas S, Coyle DJ, Dahn JJ, Burns JC. 2013. Accurate and precise temperature-controlled boxes for the safe testing of advanced automotive li-ion cells with high precision. Journal of the Electrochemical Society 160(2):A251–A258.

DOT [US Department of Transportation]. 2008. Laboratory Test Procedure for FMVSS 305, Electric Powered Vehicles: Electrolyte Spillage and Electrical Shock Protection, TP-305-01. Washington.

Doughty DH, Crafts CC. 2005. FreedomCAR Electrical Energy Storage System Abuse Test Manual for Electric and Hybrid Vehicle Applications, SAND2005-3123. Albuquerque: Sandia National Laboratories.

Ford H. 1988. Today and Tomorrow: Commemorative Edition of Ford's 1926 Classic. Cambridge: Productivity Press.

INEEL [Idaho National Engineering and Environmental Laboratory]. 2003. FreedomCAR Battery Test Manual for Power Assist Hybrid Electric Vehicles, DOE/ID-11069. Idaho Falls: US Department of Energy.

Sahraei E, Meier J, Wierzbicki T. 2014. Characterizing and modeling mechanical properties and onset of short circuit for three types of lithium-ion pouch cells. Journal of Power Sources 247:503–516.

Smith AJ, Burns JC, Trussler S, Dahn JR. 2010. Precision measurements of the coulombic efficiency of lithium-ion batteries and of electrode materials for lithium-ion batteries. Journal of the Electrochemical Society 157(2):A196–A202.

UNECE [United Nations Economic Commission for Europe]. 2013. Electric Power Trained Vehicles. Regulation No. 100, Rev. 2. Geneva.

*Research is being conducted to address materials, manufacturing, and cost challenges that hamper broader use of lithium ion batteries.*

# Lithium Ion Batteries and Their Manufacturing Challenges

Claus Daniel is deputy director of the Sustainable Transportation Program at Oak Ridge National Laboratory and associate professor of materials science in the Bredesen Center at the University of Tennessee at Knoxville.

Claus Daniel

There is no single lithium ion battery. With the variety of materials and electrochemical couples available, it is possible to design battery cells specific to their applications in terms of voltage, state of charge use, lifetime needs, and safety. Selection of specific electrochemical couples also facilitates the design of power and energy ratios and available energy.

Integration in a large format cell requires optimized roll-to-roll electrode manufacturing and use of active materials. Electrodes are coated on a metal current collector foil in a composite structure of active material, binders, and conductive additives, requiring careful control of colloidal chemistry, adhesion, and solidification. But the added inactive materials and the cell packaging reduce energy density. Moreover, degree of porosity and compaction in the electrode can affect battery performance.

In addition to these materials challenges, cost is a significant barrier to widespread adoption of this technology. Pathways are being explored to bring batteries from the commercially available 100 Wh/kg and 200 Wh/L at $500/kWh up to 250 Wh/kg and 400 Wh/L for just $125/kWh.

### Fundamentals of Lithium Ion Batteries

The lithium ion battery was made possible by the discovery of lithium cobalt oxide ($LiCoO_2$), which allows the extraction of lithium ions and creation of large amounts of vacancies (without a crystal change) up to the removal of half of the existing ions. The pairing of $LiCoO_2$ with graphite allows the intercalation of lithium ions between the graphene layers that occupy the interstitial site between every hexagonal ring of carbon atoms (Besenhard and Schöllhorn 1976; Mizushima et al. 1980; Whittingham 1976).

The lithium ions travel during charge from the positive electrode (the cathode) through a solid or liquid electrolyte to the negative electrode (the anode) and, during discharge, in the opposite direction. At each electrode, the ion either maintains its charge and intercalates into the crystal structure occupying interstitial sites in existing crystals on the anode side or reoccupies a vacant site in the cathode that formed when the lithium ion left that crystal. While transferring the ion, the host matrix gets reduced or oxidized, which releases or captures an electron.[1]

*Higher amounts of lithium enable higher capacity and voltage, but they are associated with stability problems.*

### Variety of Cathode Materials

The search for new cathode materials is driven in part by important disadvantages of $LiCoO_2$. The battery has a core temperature of 40–70°C and may be susceptible to some low-temperature reactions. But at 105–135°C it is very reactive and an excellent oxygen source for a safety hazard called a *thermal runaway reaction*, in which highly exothermic reactions create temperature spikes and accelerate rapidly with the release of extra heat (Roth 2000).

Replacement materials for $LiCoO_2$ are less prone to that failure. The compounds replace parts of the cobalt with nickel and manganese to form $Li(Ni_xMn_yCo_z)O_2$ compounds (with $x + y + z = 1$), often referred to as NMC as they contain nickel, manganese, and cobalt; or they exhibit a completely new structure in the form of phosphates (e.g., $LiFePO_4$) (Daniel et al. 2014). These cathode materials all exhibit capacities in the range of 120–160 Ah/kg at 3.5–3.7 V, resulting in maximum energy density of up to 600 Wh/kg.

When packaged in real devices, however, much inactive material mass is added and the energy density tends to drop to 100 Wh/kg on the pack level. To push for higher energy density, researchers have sought higher capacity and higher voltage—and found them in lithium- and manganese-rich transition metal oxides. These compounds are essentially the same materials as NMC but an excess of lithium and higher amounts of manganese replace nickel and cobalt. The higher amounts of lithium (as much as 20 percent more) allow the compounds to have higher capacity (Thackeray et al. 2007) and a higher voltage, resulting in cathodes with up to 280 Ah/kg when charged up to 4.8 V. However, these new compounds show stability problems and tend to fade fast.

### Balancing of Materials in Cells

Lithium ion batteries are made of layers of porous electrodes on aluminum and copper current collector foils (Daniel 2008). The capacity of each electrode pair needs to be balanced to ensure battery safety and avoid risk of overcharge of the anode (which can result in lithium metal plating and short circuiting) or overdischarge of the cathode (which can result in a collapse of the crystal structure and loss of vacancies for lithium to reintercalate, dramatically reducing capacity).

Graphite has a theoretical capacity of 372 Ah/kg, double that of the available lithium in NMC cathodes. So in balanced lithium ion batteries, the cathodes typically exhibit double the thickness compared to the anode. This inherent flaw of the cell design causes problems with mass transport and kinetics, and thus prompted the search for high-capacity cathodes.

To increase cell-level energy density, inactive materials are being minimized in battery cells. For example, one way to reduce the current collector is to increase the thickness of the electrodes, but this further drives transport problems and requires a highly engineered porosity in the electrode.

### Cost Challenges in Manufacturing Lithium Ion Batteries

The costs of lithium ion batteries are much higher than the automotive market will bear for full penetration of electric vehicles and a cost-neutral product com-

[1] If the ion changed its state of charge, it would be called a *conversion battery* (e.g., an air battery; Daniel and Besenhard 2011).

pared to cars run by internal combustion engines. The US Department of Energy cost target for all electric vehicle batteries is $125/kWh of usable energy (DOE 2013). The current cost of commercial batteries is $400–500/kWh and their projected cost with current experimental materials is $325/kWh. Most of the cost reduction thus far has been achieved by energy density increases at similar cost to the older-generation products.

Further cost reduction is possible through optimization of manufacturing schemes. Lithium ion batteries are manufactured in sets of electrodes and then assembled in cells. Active material is mixed with polymer binders, conductive additives, and solvents to form a slurry that is then coated on a current collector foil and dried to remove the solvent and create a porous electrode coating. The solvent of choice, N-methylpyrrolidone (NMP), is considered an *indirect material* (it is needed for production but not contained in the final device), but it is expensive, exhibits flammable vapors, and is highly toxic.

The flammable vapors of NMP require all processing equipment during the production of electrodes to be explosion proof, meaning all spark-producing electrical components need to be shielded from the vapors and spaces need to be highly ventilated to keep vapor concentrations low. These measures increase the capital cost of such equipment considerably.

In addition, the electrode manufacturing plant is required to recapture the solvent from its exhaust stream, distill it, and recycle it. This is again an additional cost.

### *Cost Reduction by Water-based Processing*

The replacement of NMP by water is a tremendous opportunity to reduce cost in the production of lithium ion batteries. The cost of water is negligible compared to that of NMP; water is not flammable and does not produce flammable vapors; and water is environmentally benign. However, water is a polar solvent and its behavior is completely different from that of the nonpolar NMP. Furthermore, active materials tend to agglomerate and metal current collector surfaces are hydrophobic, making the coating process more difficult.

Knowledge of surface charges on particles (by measuring zeta potential) enables the design of surface polarity in the presence of water by introducing small amounts of surfactants. In the case of cathode intercalation compounds, polyethylene imide has been successfully used to introduce a surface charge large enough to repel particles so that they do not form unacceptable agglomerates (Li et al. 2013).

Understanding the surface energy of metals and the surface tension of the slurry as well as their interaction allows for optimization of the pair. Atmospheric plasma treatment of the metal surface through exposure to a corona plasma removes organic compounds on the surface and enables a slight etching and oxidation, which dramatically reduces the surface energy to values below the surface tension of the slurry. This allows perfect wetting of the surface by the slurry and creates a coating with optimized adhesion (Li et al. 2012). The result is a 75 percent operational and materials cost reduction in the electrode manufacturing and a potential cost reduction of up to 20 percent at the battery pack level for automotive applications (Wood et al. 2014). This does not include the lower equipment cost: expenses associated with the plasma processing equipment are much lower than those for the solvent recovery system and the explosion-proof requirement.

*Water presents a tremendous opportunity to reduce cost in the production of lithium ion batteries, but it comes with challenges.*

### *Future Opportunities for Cost Reduction*

Further cost reductions will be achieved through greater knowledge of transport mechanisms and electrode architecture implications for electrochemical performance. Current research is largely focused on modeling and simulation to understand molecular mechanisms and improve the design of electrodes, electrode stacks, and battery cells. Thicker electrodes and a tremendous reduction in inactive materials will improve energy density at lower cost, reduce direct costs, and possibly enable much shorter and less energy intensive battery formation cycling.

## Conclusion

Lithium ion batteries have tremendous potential for enabling partial to full electrification of the automotive fleet, diversifying energy sources for transportation, and supporting large-scale energy storage for a higher penetration of intermittent renewable energy supply. However, cost continues to be an issue and will need to be addressed by the development of a robust supply chain, standards in manufacturing, high manufacturing throughput, and streamlined low-cost processing methods. In addition to reducing costs, research can enhance knowledge of molecular processes and transport issues in order to optimize the design and use of available energy in batteries and increase their life time.

As shown in this paper, an increase in energy content and capacity in active electrode materials and a reduction of indirect materials in production are two ways to impact cost.

## Acknowledgments

Parts of this research at Oak Ridge National Laboratory (ORNL; managed by UT Battelle, LLC) for the US Department of Energy (under contract DE-AC05-00OR22725) were sponsored by the Office of Energy Efficiency and Renewable Energy (EERE) Vehicle Technologies Office (VTO) Applied Battery Research (ABR) subprogram (program managers: Peter Faguy and David Howell). The author acknowledges many fruitful discussions with and contributions from David Wood, Jianlin Li, and Debasish Mohanty of the DOE Battery Manufacturing R&D Facility at ORNL and Beth Armstrong in ORNL's Materials Science and Technology Division.

## References

Besenhard JO, Schöllhorn R. 1976. The discharge reaction mechanism of the $MoO_3$ electrode in organic electrolytes. Journal of Power Sources 1(3):267–276.

Daniel C. 2008. Materials and processing for lithium-ion batteries. Journal of the Minerals, Metals, and Materials Society 60(9):43–48.

Daniel C, Besenhard JO, eds. 2011. Handbook of Battery Materials. Weinheim: Wiley-VCH.

Daniel C, Mohanty D, Li J, Wood DL. 2014. Cathode materials review. Review on Electrochemical Storage Materials and Technology: AIP Conference Proceedings 1597:26–43; doi: 10.1063/1.4878478.

DOE [US Department of Energy]. 2013. EV Everywhere: Grand Challenge Blueprint. Available at http://energy.gov/sites/prod/files/2014/02/f8/eveverywhere_blueprint.pdf.

Li J, Rulison C, Kiggans J, Daniel C, Wood DL. 2012. Superior performance of $LiFePO_4$ aqueous dispersions via corona treatment and surface energy optimization. Journal of the Electrochemical Society 159(8):A1152–A1157.

Li J, Armstrong BL, Kiggans J, Daniel C, Wood DL. 2013. Lithium ion cell performance enhancement using aqueous LiFePO4 cathode dispersions and polyethyleneimine dispersant. Journal of the Electrochemical Society 160(2):A201–A206.

Mizushima K, Jones PC, Wiseman PJ, Goodenough JB. 1980. $Li_xCoO_2$ (0<x<-1): A new cathode material for batteries of high energy density. Materials Research Bulletin 15(6):783–789.

Roth PE. 2000. Thermal characterization of li-ion cells using calorimetric techniques. Energy Conversion Engineering Conference and Exhibit (IECEC) 35th Intersociety 2:962–967; doi:10.1109/IECEC.2000.870897.

Thackeray MM, Kang SH, Johnson CS, Vaughey JT, Benedeka R, Hackney SA. 2007. $Li_2MnO_3$-stabilized $LiMO_2$ (M = Mn, Ni, Co) electrodes for lithium-ion batteries. Journal of Materials Chemistry 17:3112–3125.

Whittingham MS. 1976. The role of ternary phases in cathode reactions. Journal of the Electrochemical Society 123(3):315–320.

Wood DL, Li J, Daniel C. 2015. Prospects for reducing the cost of lithium ion electrode processing and cell formation steps. Journal of Power Sources 275:234–242.

*New materials, technologies, and methods are enabling the transcatheter replacement and repair of diseased heart valves.*

# The History of Heart Valves

## An Industry Perspective

Erin M. Spinner is a biomedical research engineer with Edwards Lifesciences.

Erin M. Spinner

The average heart beats 2.5 billion times in a human lifetime, during which its four valves must maintain unidirectional blood flow to maximize the heart's efficiency and provide oxygenated blood to the entire body. Although heart valves were documented by Leonardo da Vinci in some of his early sketches over 500 years ago, they have been available for implantation only since the 1950s.

Valvular disease—usually associated with advanced age, but also caused by congenital defects—can interrupt, slow, or prevent the efficient function of the valves, which lose functionality if they cannot maintain a proper seal or open completely. When any one of the valves is not working properly it may affect a person's ability to exercise or perform daily tasks and thus lead to a dramatic decrease in quality of life and even death. For these reasons, decades have been spent developing and perfecting devices to repair and replace the body's valves when they no longer function properly.

Innovation and development of replacement heart valves have largely focused on the aortic valve, which directs oxygenated blood from the left ventricle to the rest of the body. The structure of the aortic and (similar) pulmonary valves is simpler than that of the other valves—they have greater symmetry and lack the subvalvular components characteristic of the mitral and tricuspid valves—making them an attractive target for early research.

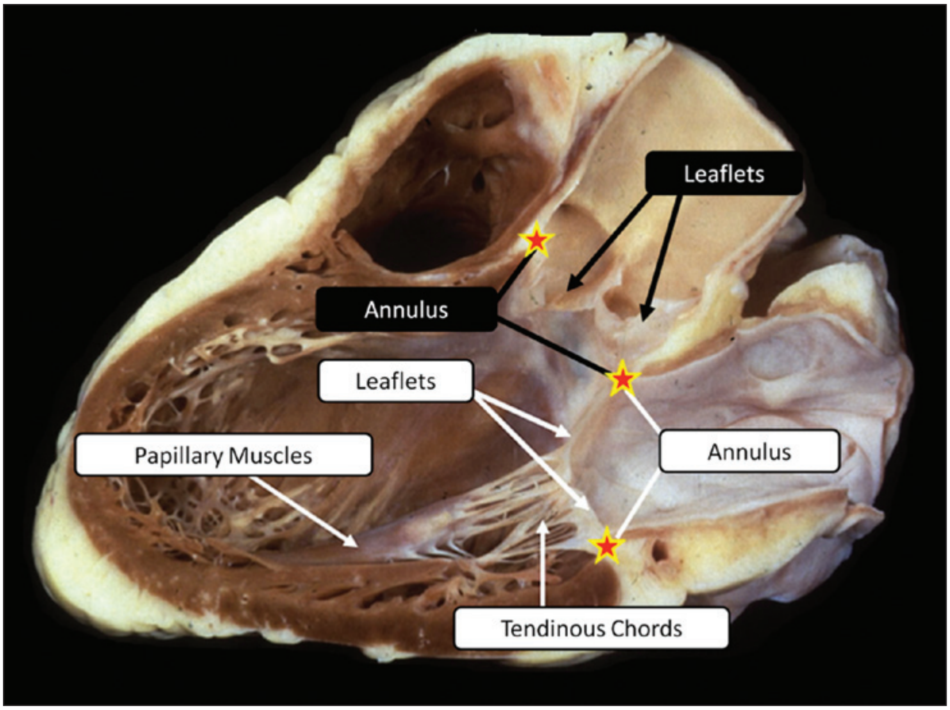



FIGURE 1 Anatomical comparison of the complexity of the aortic valve (black labels) and mitral valve (white labels). Note the subvalvular structure, including numerous chords and papillary muscles, in the mitral valve. Modified from Anderson and Kanani (2007).

The aortic and pulmonary valves consist of three leaflets of similar size and shape that are attached to the tubular vessel; in contrast, the mitral and tricuspid valves have leaflets that vary in number and size. For the mitral and tricuspid valves, these leaflets attach both directly to the wall of the ventricle at the annulus and indirectly through numerous chords (Figure 1).

Whereas past efforts focused on the aortic valve, current technologies are being developed to create devices for the more complex valves of the heart.

## Past Technologies

Valve replacement devices can be classified into two categories: whole valves and prosthetic valves. Whole valves consist of allografts and xenografts; prosthetic valves are composed of pericardial (tissue) and mechanical valves. The valve designs vary in numerous aspects and have evolved over time, but the goal has remained the same: an easily implantable and durable solution that increases blood flow while decreasing the risk of associated complications such as thrombosis. Each type of valve has advantages and disadvantages, which are taken into consideration when deciding which device is appropriate for an individual patient.

### *Whole Valves*

Allografts are valves transplanted from another human, and xenografts are from another species. Cow and pig valves are usually selected for transplant as they best mimic the size and structure of human valves.

Attempts have been made to transplant mitral valves (Gulbins et al. 2000, 2002; Kumar et al. 2000), but the most successful and frequently used valves are pulmonary and aortic valves, which are often used interchangeably due to their similar geometry. Developments in transplanted valves have focused on improving structural support, which is necessary when the valve is removed from its native surroundings (Figure 2).

Vast strides have been made in tissue cryopreservation, which maintains high cell viability when thawed (O'Brien et al. 1987). But the appeal of allograft and xenograft valves suffers from their limited availability of size ranges and technically challenging procedure, in the case of stentless designs, which require the physician to remove the entire valve along with a portion of the aortic root to attach the replacement valve.

### *Prosthetic Valves*

Transplanted whole valves remain a viable option, but prosthetic valves, including both mechanical and pericardial tissue valves, hold the largest share of the market. Of valves implanted in the United States today, most (approximately 60,000) are made of pericardial tissue; in contrast, only 10,000 mechanical valves were implanted in 2013 (Millennium Research Group 2013), although design improvements are minimizing or often eliminating the disadvantages of mechanical valves (e.g., thrombogenicity requiring anticoagulation therapy).

Both pericardial and mechanical valves consist of a sewing ring (for securing them in place), a support structure, and leaflets. Mechanical valves are similar in structure to tissue valves, but differ in the leaflet design

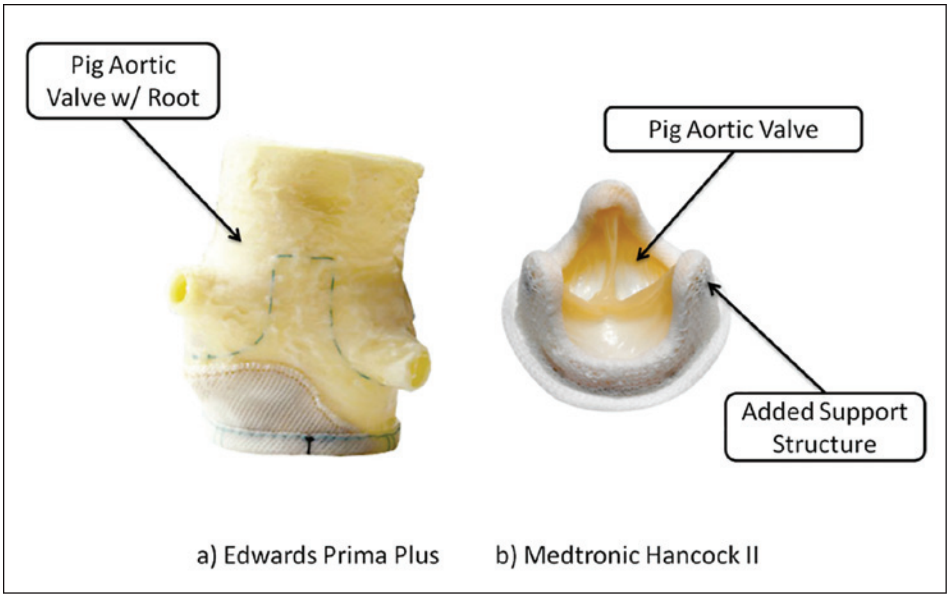



FIGURE 2 Examples of (a) stentless xenograft that uses the native support structure of the aorta and (b) supported xenograft with native aortic valve removed and added stent and sewing ring structure.

(Figure 3). Mechanical valves have seen the greatest variety in designs, optimized through geometry, hinge mechanisms, and materials.

These designs include ball and cage, floating/tilting disc, and bileaflet (Figure 3a); the latter is the leading design in today's industry. These valves do not need to be replaced—indeed, they typically outlive the patient—but they require the constant use of anticoagulants, which is not appealing to most people and not an option for some. In contrast, tissue valves lack the longevity of mechanical valves but do not require anticoagulation, making them a preferred choice.

Unlike mechanical valves, pericardial tissue, the sac that lines the heart, is highly durable and therefore used to construct the leaflets of a tissue prosthetic valve. The leaflets are then sewn to the stent support structure attached to the sewing ring. The attachment of the tissue to the structure is crucial to ensure durability and requires each valve to be hand assembled and sewn. The sewing ring may consist of a silicone band and cloth that support tissue ingrowth to the surrounding anatomy to provide future fixation support.

Although the overall design of the tissue valve has remained relatively unchanged throughout the years and mimics the design of the native aortic and pulmonary valves, the fixation process for the leaflets has been optimized. Various solutions are used to crosslink the collagen fibers and ensure durable leaflet structure. The method by which tissue is fixed and preserved is a proprietary process guarded by each company.

As with any design, tissue valves also have limitations, of which the most significant is durability. Typical tissue valves currently on the market can last up to 20 years before the leaflets lose functionality and experience structural deterioration, usually due to calcification (Schoen and Hobson 1985; Schoen and Levy 2005).

**Current Technologies**

Over the past 10 years, noninvasive implantation of heart valves has revolutionized the field. Implants traditionally required the chest to be splayed open to allow access to the heart, but recent advances make it possible to access the valve through the femoral vein via an incision as small as an inch. This noninvasive approach, called *transcatheter valve replacement*, is

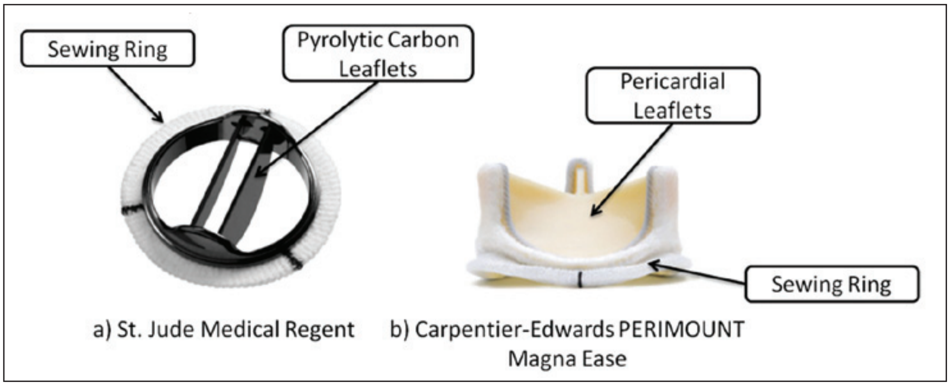



FIGURE 3 Examples of (a) bileaflet mechanical and (b) tissue prosthetic valves. Both valves shown can be used as replacements for all valves.

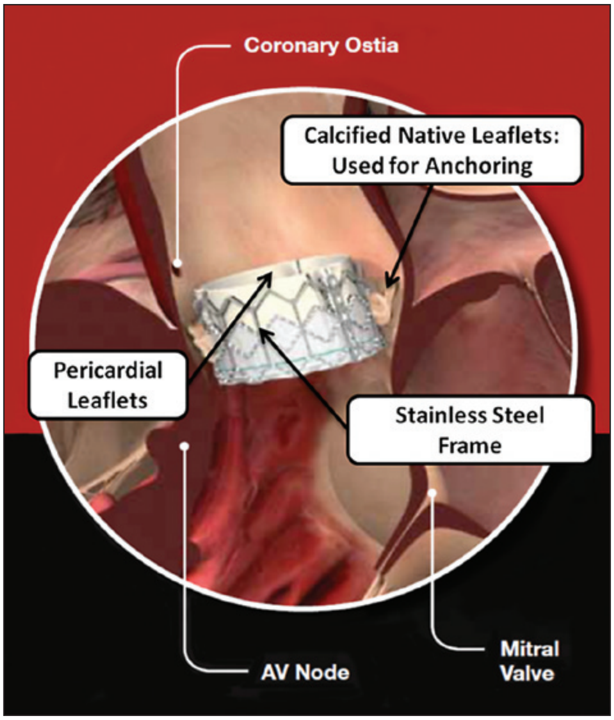



FIGURE 4 Transcatheter heart valve using the surrounding calcium in the native aortic valve to anchor. AV = atrioventricular. Source: Edwards Lifesciences.

suitable for patients who are not candidates for open-heart surgery and offers a faster recovery.

The first transcatheter delivery of a valve was attempted in the 1960s, but it has only recently become accepted as a viable procedure, aided by advances in stent design and noninvasive imaging techniques. The development of transcatheter heart valves showcases the power of a multidisciplinary approach: it merges technologies from numerous devices (e.g., coronary stents and balloon angioplasty) and disciplines (e.g., interventional cardiology and cardiac surgery) to create a paradigm-shifting advance.

There are many advantages to a transcatheter approach, but added complexity arises because the valve must work with the patient's diseased anatomy. In the past the diseased valve was typically removed; now, the designs and their ability to succeed rely heavily on the patient's anatomy. For example, a transcatheter aortic valve is secured in place by applying an outward force on the calcium deposits on the native leaflets.

An additional obstacle that transcatheter technologies have had to overcome is the loss of direct visualization afforded by open-heart surgery. This is especially important when deciding where to place the valve to ensure that it is secured while avoiding the coronary ostia, which is crucial to supplying blood to the heart (Figure 4). Advances in noninvasive imaging allow for real-time imaging using multiple modalities, such as echocardiography to visualize the native anatomy and fluoroscopy to visualize the device.

## Future Technologies

The valve replacement industry is beginning to focus on the other valves in the heart and developing devices that will work in concert with the native anatomy to repair instead of replace native valve function. The number of repair procedures is on the rise as compared to replacement procedures, which have remained steady from year to year. Recent trends favor repairing the native valve as opposed to replacing it, with approximately 32,000 mitral repairs as compared to 21,000 replacement procedures conducted in the United States in 2013 (Millennium Research Group 2013).

The introduction of transcatheter heart valves has brought new excitement to this area. Placed inside a defective tissue valve, transcatheter valves provide a way around the challenge of tissue valve durability: a tissue valve may be implanted in a younger patient with the idea that an additional valve can be placed if needed at a later date.

Valve manufacturers are expanding the number of diseases they can treat through transcatheter technologies; for example, companies are working to treat mitral valve regurgitation, a much larger market compared to aortic valve pathology. But, as mentioned, there are many hurdles in the transfer of technology and techniques to the mitral valve because it is more complex and patients tend to be in worse overall health with multiple comorbidities. That said, technology has advanced such that it is possible to attack more subtle pathologies and not only a valve that is completely failing.

Mitral valve repair technologies today aim at correcting a specific pathology and do so by targeting any aspect of the valve, from replacing the chords, which attach the leaflets to the ventricle, to reducing the size of the annulus and bringing the leaflets closer together to allow for sealing. In attempts to replace the valve, designs require an anchoring location as they cannot be sewn in like a traditional surgical replacement. Engineers therefore retain the native leaflets or annulus when possible as an anchor site for the replacement part.

Because of the direct interaction with and reliance on the functionality of the native valve, engineers must expand their horizons and become experts in tissue mechanics as well. The frontier of heart valve engineering is less about engineering and more about applying engineering principles in a way that requires understanding of anatomy and physiology. Collaborations of engineers working side by side with clinicians, biomedical engineers, and biologists produce the best heart valve designs.

The future of heart valves is also reliant on new engineering materials. In addition to progress in the application of synthetic materials, especially with the mechanical valve, new biological and polymeric materials are being developed. With the advent of transcatheter valves, the limits of current materials are being challenged. Tissue, polymeric, and even cloth designs are being pushed beyond what was previously thought possible in the effort to increase strength and durability and reduce the device profile. The latter requires thinner leaflets, which in turn require ingenuity to develop a strong but thin material.

New tissue treatment processes are also being developed and tested. A recent advance allows valves to be shipped dry, no longer requiring the leaflets to be stored in solution. This development allows transcatheter valves to be shipped on the delivery catheter and eliminates the need for an engineer to be present at the procedure.

These examples are a testament to the benefits of new technologies: they both enable and force development beyond what was previously thought possible.

**Designing for the Future**

Next generation heart valves have brought excitement to the field, but it is also important to understand how we as engineers go from a concept to a life-saving device. We must first survey the patient population and identify a need, then develop a concept to address that need. Bench studies and animal studies are used in conjunction to test the functionality and durability of a design. Then the materials are tested in animal models to ensure that no adverse effects arise as a result of interactions with the body.

Complementing innovations in materials and design, new imaging protocols are being developed to ensure that a device is delivered to the correct location. Using a combination of imaging techniques (e.g., echocardiography, angiography, MRI, and CT), the implantation team can visualize both the device and the anatomy without opening the chest. These techniques are also used to determine the success of the procedure both at the time of implantation and in follow-up examinations to ensure the device's continued functionality.

When heart valves were first implanted, regulatory requirements to review the process for implantation were minimal or nonexistent. Now extensive testing is required to ensure short- and long-term success prior to implantation. The test data are submitted to a regulatory body and reviewed before implantation can be cleared. Pending full approval for general use, a first-in-human study may be conducted in compassionate cases, for patients who have no other options; these trials are usually limited to about 10 patients. If they show success a much larger clinical study is initiated, which can include hundreds of patients. From there the data are submitted to the regulatory body to get approval to commercialize the device and make it accessible to the approved patient population, ensuring that the patient's safety is the priority. When the device is made available for the masses it fulfills its original goal of saving lives.

As with many engineering creations, the design process is never complete. Once the device is implanted in humans, improvements are constantly made based on evidence from the patients. Research and development efforts seek to recreate and simulate the human environment on the bench and in animals, but there are always lessons to be learned and from there improvements.

*Using a combination of imaging techniques, the implantation team can visualize both the device and the anatomy without opening the chest.*

Additionally, as new technologies and innovations are introduced to the marketplace, even in different industries, these are applied to existing devices for optimization as necessary. A great example of this is the development of new biomaterials for orthopaedic and other cardiovascular applications, in which findings and testing history can be leveraged for the valve area.

## Conclusions

Now is an exciting time for heart valve development as companies are pushing the limits, expanding into new areas, and helping more patients than ever before. Advances continue to move heart valve development forward. As designs are optimized engineers are turning their attention to other disease states with next generation designs and approaches. With increased confidence in current device durability for both mechanical and tissue valves, the focus is changing from surgical to transcatheter implants and from replacement to repair devices implanted with transcatheter methods.

Each advance requires greater understanding of the disease state of the valve. The greatest successes will involve technologies and techniques that work in concert with the human body.

## References

Anderson RH, Kanani M. 2007. Mitral valve repair: Critical analysis of the anatomy discussed. Multimedia Manual of Cardiothoracic Surgery (MMCTS)/European Association for Cardio-Thoracic Surgery 2007(0219):mmcts 2006 002147.

Gulbins H, Kreuzer E, Uhlig A, Reichart B. 2000. Mitral valve surgery utilizing homografts: Early results. Journal of Heart Valve Disease 9:222–229.

Gulbins H, Anderson I, Kilian E, Schrepfer S, Uhlig A, Kreuzer E, Reichart B. 2002. Five years of experience with mitral valve homografts. Thoracic and Cardiovascular Surgeon 50:223–229.

Kumar AS, Choudhary SK, Mathur A, Saxena A, Roy R, Chopra P. 2000. Homograft mitral valve replacement: Five years' results. Journal of Thoracic and Cardiovascular Surgery 120:450–458.

Millennium Research Group. 2013. US markets for heart valve devices 2014. Available at www.mrg.net/Products-and-Services/Syndicated-Report.aspx?r=RPUS12HV13.

O'Brien MF, Stafford EG, Gardner MA, Pohlner PG, McGiffin DC. 1987. A comparison of aortic valve replacement with viable cryopreserved and fresh allograft valves, with a note on chromosomal studies. Journal of Thoracic and Cardiovascular Surgery 94:812–823.

Schoen FJ, Hobson CE. 1985. Anatomic analysis of removed prosthetic heart valves: Causes of failure of 33 mechanical valves and 58 bioprostheses, 1980 to 1983. Human Pathology 16:549–559.

Schoen FJ, Levy RJ. 2005. Calcification of tissue heart valve substitutes: Progress toward understanding and prevention. Annals of Thoracic Surgery 79:1072–1080.

*Injectable biomaterials are being developed as a minimally invasive approach to decrease damage after a heart attack.*

# Biomaterials for Treating Myocardial Infarctions

Jason A. Burdick

Shauna M. Dorsey

Jason A. Burdick and
Shauna M. Dorsey

Biomaterials are gaining attention in the development of biomedical therapies for treating patients after a myocardial infarction (i.e., heart attack). These materials may serve as mechanical restraints, vehicles for the delivery of therapeutics, or 3-dimensional scaffolds for tissue regeneration. This article focuses on one particular class of materials: injectable hydrogels, natural or synthetic water-swollen polymer networks that are a promising therapy to attenuate ventricular remodeling after myocardial infarction. They act both as acellular bulking agents to mechanically stabilize the myocardium and as delivery vehicles for cells and/or therapeutic molecules. Various materials, cells, and therapeutic molecules have demonstrated positive outcomes in the repair of cardiac tissue after infarction and provide insight for future material development and optimization. Further development of injectable hydrogels for cardiac repair will have considerable clinical impact by improving therapies to prevent progression to heart failure.

## Overview of Heart Disease

Heart failure affects almost 23 million individuals worldwide (Bui et al. 2011), and nearly 70 percent of these cases are due to coronary artery

---

Jason A. Burdick is a professor and Shauna M. Dorsey a PhD candidate in the Department of Bioengineering at the University of Pennsylvania.

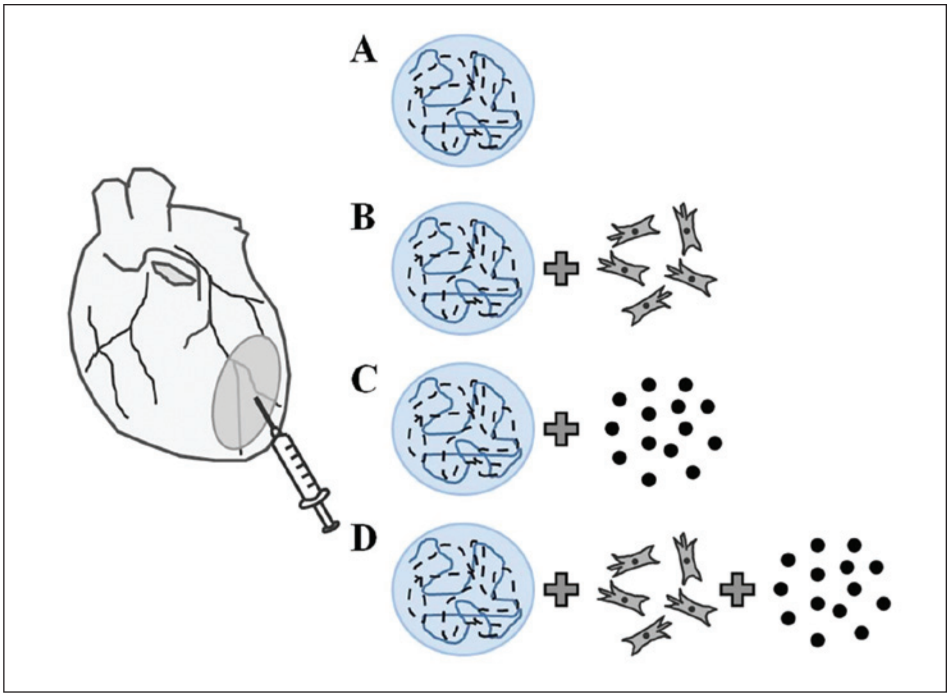



FIGURE 1 Injectable hydrogel approaches for the treatment of myocardial infarction. Hydrogels (shown in the center column) can be used as (A) acellular bulking agents or a vehicle for delivery of (B) cells, (C) therapeutic molecules, or (D) a combination of cells and molecules.

disease, which causes myocardial infarction (MI) (Go et al. 2014). MI occurs after coronary artery occlusion, resulting in depletion of nutrients and oxygen to the cardiac tissue and subsequent cell death (Cleutjens and Creemers 2002). The death of cells (i.e., cardiomyocytes) leads to the recruitment of inflammatory cells to remove the necrotic debris and the activation of bioactive molecules such as matrix metalloproteinases, which in turn cause degradation of the extracellular matrix (ECM) in cardiac tissue, weakening the myocardial wall and making it susceptible to global geometric changes, including thinning and dilation (Buckberg 2005; Dobaczewski et al. 2010; Holmes et al. 2005; Nahrendorf 2011; Spinale 2007). Infarct expansion occurs after the initial problems and is a progressive pathologic process that causes abnormal stress distributions in the borderzone regions surrounding the infarct. The process, additional cell death, and increases in borderzone stress are termed *left ventricular (LV) remodeling* and can lead to altered contractile properties and heart failure (Epstein et al. 2002; Jackson et al. 2003; Pilla et al. 2005).

## Treatment Strategies

Building on understanding of the biological and mechanical processes after MI, many strategies now utilize biomaterials for patient treatment. Several focus on treatment after significant tissue remodeling; for example, with tissue engineering, replacement cardiac tissue is developed in the laboratory and then implanted to replace damaged tissue. Another promising approach involves treating the tissue during the acute phase to try to attenuate the remodeling response before significant damage.

One option is to limit the initial infarct expansion, which has been identified as associated with the LV remodeling that leads to heart failure. Previous strategies to limit infarct expansion involved surgical reconstruction of the dilated LV and physical restraint of the ventricle or infarct region using polymeric meshed materials to prevent dilation (Batista et al. 1997; Klodell et al. 2008; Starling et al. 2007), but these approaches are highly invasive and require open-chest surgery.

Injectable biomaterials are being developed as a minimally invasive alternative to decrease damage to surrounding tissues. Among numerous potentially injectable biomaterials (e.g., microparticles), injectable hydrogels are particularly promising; they are water-swollen networks of polymer chains that have a high degree of tunability and can be formed through numerous crosslinking mechanisms (Ruel-Gariepy and Leroux 2004). They have been shown to mechanically stabilize the myocardial wall and modulate LV remodeling either alone or through the delivery of therapies such as cells and growth factors (Figure 1) (Nelson et al. 2011; Tous et al. 2011).

### *Acellular Approaches*

Many investigators believe that post-MI regional mechanical changes and stresses in the myocardium should be addressed when designing biomaterial-based approaches for cardiac repair (Gupta et al. 1994; Holmes et al. 2005; Nelson et al. 2011). As described by the Law of Laplace (Equation 1), stress ($T$) is directly proportional to pressure ($P$) and the radius of curvature ($R$) and inversely proportional to the myocardial thickness ($h$). Therefore, the increase in $R$ and decrease in $h$ that occur after MI lead to an increase in $T$.

$$T = \frac{P * R}{h} \quad (1)$$

Injectable biomaterials can limit infarct expansion by bulking the damaged myocardial wall through mechanical stabilization (Tous et al. 2011). Infarcts naturally stiffen over time as wound healing progresses and collagen is deposited; modifying the tissue properties of the infarct region before the body compensates for the remodeling process can limit infarct expansion and post-MI remodeling (Tous et al. 2011). Injectable hydrogels act as bulking agents by increasing the myocardial wall thickness ($h$) to decrease LV dilation (as measured by $R$) and in turn decrease wall stress ($T$). Theoretical finite element models have confirmed this mechanism of treatment by demonstrating that hydrogels decrease both LV dilation and myofiber stresses (Wall et al. 2006).

Injectable hydrogels can be grouped into either natural or synthetic materials. Natural materials offer advantages such as inherent biological properties, including receptor-binding ligands and susceptibility to proteolytic degradation (Karam et al. 2012; Lutolf and Hubbell 2005). For cardiac applications where the goal is to replace or repair the damaged ECM, natural biomaterials more closely mimic features of the native ECM and can also be therapeutic in their degradation products through the recruitment of cells (Sui et al. 2011). Commonly used natural injectable materials for cardiac repair are fibrin, alginate, collagen, Matrigel, chitosan, hyaluronic acid, keratin, and decellularized matrices (Tous et al. 2011). But natural materials have limited tunability in properties.

Synthetic materials have defined material properties such as molecular weight, gelation, hydrophilic/hydrophobic properties, degradation, and mechanics, without batch-to-batch variations (Lutolf and Hubbell 2005). They can also be modified with cell binding sites or adhesive ligands to encourage cell interaction (Davis et al. 2005). Various synthetic materials have been explored for cardiac repair therapy, including poly(N-isopropylacrylamide) (PNIPAm)- and poly(ethylene glycol) (PEG)-based hydrogels (Tous et al. 2011). An example of an injected hydrogel based on hyaluronic acid is shown in Figure 2.

*Cellular Approaches*

Myocardial infarction results in the loss of over 1 billion cardiomyocytes in the infarct region, and cell delivery is one strategy used for tissue repair (Beltrami et al. 1994). A variety of cell types have been delivered—fetal or neonatal cardiomyocytes, embryonic stem cells (ESCs), skeletal myoblasts, bone marrow–derived stem cells (BSCs), adipose-derived stem cells, and cardiac stem cells (Menasche 2005; Segers and Lee 2008). Each has advantages and disadvantages for use in therapies. For example, ESCs offer the advantage of differentiating into both cardiomyocyte and vascular lineages, but their efficacy is limited because of their immunogenicity, risk of tumor development, and ethical concerns (Zimmermann 2011). BSCs are an autologous option that can be readily isolated and delivered to cardiac tissue, but their fate is not clear (Le Blanc and Pittenger 2005).

Although both animal models (Segers and Lee 2008) and clinical studies (Menasche 2005) have demonstrated some enhancement in cardiac function with cell delivery, these improvements are often insufficient and transient, effects that are believed to result from unsatisfactory cell retention, survival, and engraftment (D'Alessandro and Michler 2010). For example, less

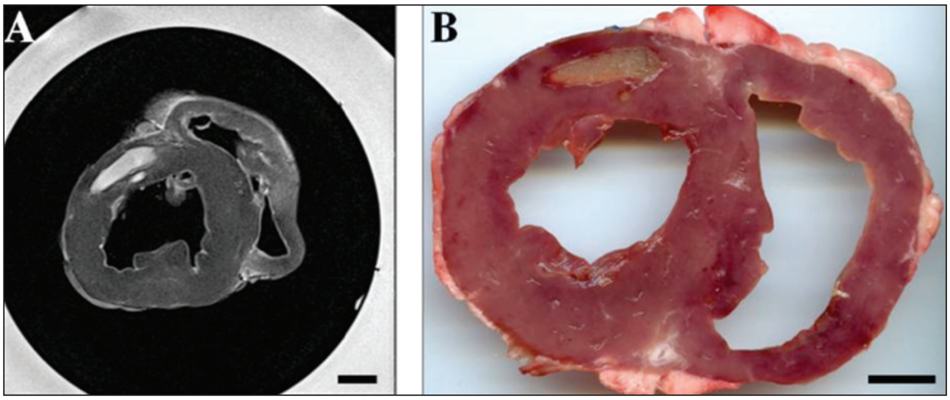



FIGURE 2 Acellular hydrogels as bulking agents for myocardial infarction repair. Injectable hyaluronic acid hydrogel distribution in cardiac tissue explant as shown by (A) magnetic resonance imaging and (B) ex vivo sectioning. Scale bar = 1 cm.

than 10 percent of BSCs delivered have been detected two hours after injection (Hofmann et al. 2005; Hou et al. 2005), and of those that stay at the injury site approximately 90 percent die within the first week because of physical stress, ischemia (due to microvasculature obstruction), inflammation, and release of cytokines and reactive oxygen species (Robey et al. 2008).

Injectable hydrogels have been explored to enhance cell retention and engraftment for cardiac repair by improving cell attachment, migration, and survival upon delivery (Huang et al. 2005). They permit both high encapsulation efficiency (cells are entrapped during gelation) and precise control over the biophysical and biochemical microenvironment surrounding cells after delivery (Bian et al. 2009).

As with acellular hydrogels, both synthetic and natural polymers have been investigated. Natural materials, such as fibrin, alginate, collagen, and Matrigel, are a popular choice for cell delivery because their inherent biological activity initiates cell-biomaterial interactions (Tous et al. 2011). Synthetic hydrogels can also be used to deliver cells for cardiac repair. With their tunability, synthetic materials can be modified to control both adhesion for cell retention and degradation for desired timing of cell release into the tissue environment. As with the acellular hydrogels, the primary synthetic materials used for cell delivery are PNIPAm and PEG (Tous et al. 2011).

## Injectable Hydrogels for Molecule Delivery

In addition to the approaches described above to alter local mechanical stabilization and serve as a cell delivery vehicle, injectable hydrogels can deliver therapeutic molecules to address post-MI LV remodeling.

Tissue repair is a complex process controlled in part by numerous molecules, such as growth factors and cytokines, and the delivery of such molecules can modulate post-MI endogenous biological responses (Segers and Lee 2010). Delivery of therapeutic molecules alone, by either direct myocardial injection or systemic intravenous circulation, has helped restore cardiac function in some animal models, but the short half-life of the molecules and off-target complications limit clinical application (Urbanek et al. 2005).

Because of these limitations, injectable hydrogels have been used as delivery vehicles to localize molecules and tailor release kinetics through changes in polymer-molecule interactions, polymer hydrophobicity, and hydrogel degradation (Chen and Mooney 2003; Kretlow et al. 2007). Hydrogels can both sustain local molecule release and prolong molecule bioactivity (Langer and Folkman 1976). For cardiac applications, injectable hydrogels are useful to deliver antiapoptotic molecules (which limit cell death after injury), angiogenic factors to promote vessel formation, or chemoattractants to recruit cells for repair and attenuation of post-MI remodeling (Tous et al. 2011).

## Looking Forward

As discussed here, a range of injectable hydrogels, cell types, and molecules have been delivered with the intent of attenuating LV remodeling after myocardial infarction. Although many hydrogels have shown positive outcomes in animal models, only one (alginate) has progressed to clinical trials.[1] Research is needed to elucidate the effects of hydrogel properties, mode of delivery (e.g., direct injection vs. catheter delivery), and timing of delivery (e.g., acute vs. chronic MI) on LV remodeling. Future studies should further investigate the mechanisms by which hydrogels act on the heart, including both biological and mechanical effects, and focus on clinically relevant parameters to optimize repair outcomes.

## References

Batista RJ, Verde J, Nery P, Bocchino L, Takeshita N, Bhayana JN, Bergsland J, Graham S, Houck JP, Salerno TA. 1997. Partial left ventriculectomy to treat end-stage heart disease. Annals of Thoracic Surgery 64(3):634–638.

Beltrami CA, Finato N, Rocco M, Feruglio GA, Puricelli C, Cigola E, Quaini F, Sonnenblick EH, Olivetti G, Anversa P. 1994. Structural basis of end-stage failure in ischemic cardiomyopathy in humans. Circulation 89(1):151–163.

Bian W, Liau B, Badie N, Bursac N. 2009. Mesoscopic hydrogel molding to control the 3D geometry of bioartificial muscle tissues. Nature Protocols 4(10):1522–1534.

Buckberg GD. 2005. Architecture must document functional evidence to explain the living rhythm. European Journal of Cardio-Thoracic Surgery 27(2):202–209.

Bui AL, Horwich TB, Fonarow GC. 2011. Epidemiology and risk profile of heart failure. Nature Reviews Cardiology 8(1):30–41.

[1] Information about the trials is available at http://clinicaltrials.gov/ct2/show/NCT01226563 ("IK-5001 for the Prevention of Remodeling of the Ventricle and Congestive Heart Failure after Acute Myocardial Infarction") and at http://clinicaltrials.gov/ct2/results?term=Safety+and+Feasibility+of+the+Injectable+BL-1040+Implant&Search=Search.

Chen RR, Mooney DJ. 2003. Polymeric growth factor delivery strategies for tissue engineering. Pharmaceutical Research 20(8):1103–1112.

Cleutjens JP, Creemers EE. 2002. Integration of concepts: Cardiac extracellular matrix remodeling after myocardial infarction. Journal of Cardiac Failure 8(6 Suppl):S344–S348.

D'Alessandro DA, Michler RE. 2010. Current and future status of stem cell therapy in heart failure. Current Treatment Options in Cardiovascular Medicine 12(6):614–627.

Davis ME, Hsieh PC, Grodzinsky AJ, Lee RT. 2005. Custom design of the cardiac microenvironment with biomaterials. Circulation Research 97(1):8–15.

Dobaczewski M, Gonzalez-Quesada C, Frangogiannis NG. 2010. The extracellular matrix as a modulator of the inflammatory and reparative response following myocardial infarction. Journal of Molecular and Cellular Cardiology 48(3):504–511.

Epstein FH, Yang Z, Gilson WD, Berr SS, Kramer CM, French BA. 2002. MR tagging early after myocardial infarction in mice demonstrates contractile dysfunction in adjacent and remote regions. Magnetic Resonance in Medicine 48(2):399–403.

Go AS, Mozaffarian D, Roger VL, Benjamin EJ, Berry JD, Blaha MJ, Dai S, Ford ES, Fox CS, Franco S, Fullerton HJ, Gillespie C, Hailpern SM, Heit JA, Howard VJ, Huffman MD, Judd SE, Kissela BM, Kittner SJ, Lackland DT, Lichtman JH, Lisabeth LD, Mackey RH, Magid DJ, Marcus GM, Marelli A, Matchar DB, McGuire DK, Mohler ER 3rd, Moy CS, Mussolino ME, Neumar RW, Nichol G, Pandey DK, Paynter NP, Reeves MJ, Sorlie PD, Stein J, Towfighi A, Turan TN, Virani SS, Wong ND, Woo D, Turner MB, American Heart Association Statistics Committee and Stroke Statistics Subcommittee. 2014. Heart disease and stroke statistics–2014 update: A report from the American Heart Association. Circulation 129(3):e28–e292.

Gupta K, Ratcliffe M, Fallert M, Edmunds L, Bogen D. 1994. Changes in passive mechanical stiffness of myocardial tissue with aneurysm formation. Circulation 89(5):2315–2326.

Hofmann M, Wollert KC, Meyer GP, Menke A, Arseniev L, Hertenstein B, Ganser A, Knapp WH, Drexler H. 2005. Monitoring of bone marrow cell homing into the infarcted human myocardium. Circulation 111(17):2198–2202.

Holmes JW, Borg TK, Covell JW. 2005. Structure and mechanics of healing myocardial infarcts. Annual Review of Biomedical Engineering 7:223–253.

Hou D, Youssef EA, Brinton TJ, Zhang P, Rogers P, Price ET, Yeung AC, Johnstone BH, Yock PG, March KL. 2005. Radiolabeled cell distribution after intramyocardial, intracoronary, and interstitial retrograde coronary venous delivery: Implications for current clinical trials. Circulation 112(9 Suppl):I150–I156.

Huang NF, Yu J, Sievers R, Li S, Lee RJ. 2005. Injectable biopolymers enhance angiogenesis after myocardial infarction. Tissue Engineering 11(11–12):1860–1866.

Jackson BM, Gorman JH 3rd, Salgo IS, Moainie SL, Plappert T, St John-Sutton M, Edmunds LH Jr, Gorman RC. 2003. Border zone geometry increases wall stress after myocardial infarction: Contrast echocardiographic assessment. American Journal of Physiology: Heart and Circulatory Physiology 284(2):H475–H479.

Karam JP, Muscari C, Montero-Menei CN. 2012. Combining adult stem cells and polymeric devices for tissue engineering in infarcted myocardium. Biomaterials 33(23):5683–5695.

Klodell CT Jr, Aranda JM Jr, McGiffin DC, Rayburn BK, Sun B, Abraham WT, Pae WE Jr, Boehmer JP, Klein H, Huth C. 2008. Worldwide surgical experience with the Paracor HeartNet cardiac restraint device. Journal of Thoracic and Cardiovascular Surgery 135(1):188–195.

Kretlow JD, Klouda L, Mikos AG. 2007. Injectable matrices and scaffolds for drug delivery in tissue engineering. Advanced Drug Delivery Reviews 59(4–5):263–273.

Langer R, Folkman J. 1976. Polymers for the sustained release of proteins and other macromolecules. Nature 263(5580):797–800.

Le Blanc K, Pittenger M. 2005. Mesenchymal stem cells: Progress toward promise. Cytotherapy 7(1):36–45.

Lutolf M, Hubbell J. 2005. Synthetic biomaterials as instructive extracellular microenvironments for morphogenesis in tissue engineering. Nature Biotechnology 23(1):47–55.

Menasche P. 2005. Stem cells for clinical use in cardiovascular medicine: Current limitations and future perspectives. Thrombosis and Haemostasis 94(4):697–701.

Nahrendorf M. 2011. Imaging of infarct healing predicts left ventricular remodeling and evolution of heart failure: Focus on protease activity. Circulation: Cardiovascular Imaging 4(4):351–353.

Nelson DM, Ma Z, Fujimoto KL, Hashizume R, Wagner WR. 2011. Intra-myocardial biomaterial injection therapy in the treatment of heart failure: Materials, outcomes and challenges. Acta Biomaterialia 7(1):1–15.

Pilla JJ, Blom AS, Gorman JH 3rd, Brockman DJ, Affuso J, Parish LM, Sakamoto H, Jackson BM, Acker MA, Gorman RC. 2005. Early postinfarction ventricular restraint improves borderzone wall thickening dynamics during remodeling. Annals of Thoracic Surgery 80(6): 2257–2262.

Robey TE, Saiget MK, Reinecke H, Murry CE. 2008. Systems approaches to preventing transplanted cell death in cardiac repair. Journal of Molecular and Cellular Cardiology 45(4):567–581.

Ruel-Gariepy E, Leroux JC. 2004. In situ-forming hydrogels: Review of temperature-sensitive systems. European Journal of Pharmaceutics and Biopharmaceutics 58(2):409–426.

Segers VF, Lee RT. 2008. Stem-cell therapy for cardiac disease. Nature 451(7181):937–942.

Segers VF, Lee RT. 2010. Protein therapeutics for cardiac regeneration after myocardial infarction. Journal of Cardiovascular Translational Research 3(5):469–477.

Spinale FG. 2007. Myocardial matrix remodeling and the matrix metalloproteinases: Influence on cardiac form and function. Physiological Reviews 87(4):1285–1342.

Starling RC, Jessup M, Oh JK, Sabbah HN, Acker MA, Mann DL, Kubo SH. 2007. Sustained benefits of the CorCap Cardiac Support Device on left ventricular remodeling: Three year follow-up results from the Acorn clinical trial. Annals of Thoracic Surgery 84(4):1236–1242.

Sui R, Liao X, Zhou X, Tan Q. 2011. The current status of engineering myocardial tissue. Stem Cell Reviews 7(1):172–180.

Tous E, Purcell B, Ifkovits JL, Burdick JA. 2011. Injectable acellular hydrogels for cardiac repair. Journal of Cardiovascular Translational Research 4(5):528–542.

Urbanek K, Rota M, Cascapera S, Bearzi C, Nascimbene A, De Angelis A, Hosoda T, Chimenti S, Baker M, Limana F, Nurzynska D, Torella D, Rotatori F, Rastaldo R, Musso E, Quaini F, Leri A, Kajstura J, Anversa P. 2005. Cardiac stem cells possess growth factor-receptor systems that after activation regenerate the infarcted myocardium, improving ventricular function and long-term survival. Circulation Research 97(7):663–673.

Wall ST, Walker JC, Healy KE, Ratcliffe MB, Guccione JM. 2006. Theoretical impact of the injection of material into the myocardium: A finite element model simulation. Circulation 114(24):2627–2635.

Zimmermann WH. 2011. Embryonic and embryonic-like stem cells in heart muscle engineering. Journal of Molecular and Cellular Cardiology 50(2):320–326.

*Manufacturers of innovative medical technologies for the heart can leverage different tools and techniques to meet regulatory requirements and get their devices to the market.*

# Regulatory Perspectives on Technologies for the Heart

Tina M. Morrison

Tina M. Morrison is regulatory advisor of computational modeling in the Center for Devices and Radiological Health at the US Food and Drug Administration.

With advances in materials science, manufacturers are able to develop medical devices[1] from stronger, superelastic materials and tissue (patient-specific or otherwise), opening the door for less invasive surgical therapies and personalized medicine. Moreover, access to computers with substantial processing power enables manufacturers to use computational tools paired with patient-specific diagnostic images to simulate treatment options, almost in real time. In addition, with the increasing cost of health care alongside the aging baby boomer population, there is a need to improve quality of life, decrease the number of doctor visits and length of

---

Note: The symposium presentation on regulatory perspectives was given by Sonna Patel-Raman of Halloran Consulting Group, Inc.

[1] The FDA (www.fda.gov/aboutfda/transparency/basics/ucm211822.htm) defines a medical device as "an instrument, apparatus, implement, machine, contrivance, implant, *in vitro* reagent, or other similar or related article, including a component part, or accessory which is:

- intended for use in the diagnosis of disease or other conditions, or in the cure, mitigation, treatment, or prevention of disease, in man or other animals, or
- intended to affect the structure or any function of the body of man or other animals, and which does not achieve any of its primary intended purposes through chemical action within or on the body of man or other animals and which is not dependent upon being metabolized for the achievement of any of its primary intended purposes."

**BOX 1**
**America's Heart Disease Burden**

- About 600,000 people die of heart disease in the United States every year—that's 1 in every 4 deaths (Murphy et al. 2013).
- Heart disease is the leading cause of death for both men and women. More than half of the deaths due to heart disease in 2009 were in men (Murphy et al. 2013).
- Coronary heart disease is the most common type of heart disease, killing nearly 380,000 people annually (Murphy et al. 2013).
- Every year about 720,000 Americans have a heart attack; of these, 205,000 have already had one (Go et al. 2014).
- Coronary heart disease alone costs the United States $108.9 billion each year (Heidenreich et al. 2011) in healthcare services, medications, and lost productivity.

hospital stays, and provide more efficient treatment options that reduce costs for people living with heart disease, as highlighted in Box 1.

The objectives of this paper are to explain the regulatory process for medical devices from an engineering perspective, how manufacturers of medical devices can leverage different tools and techniques to get their devices to the market, and how regulators might evaluate innovative medical technologies for the heart.

## Background

The US Food and Drug Administration's Center for Devices and Radiological Health (CDRH) is responsible for regulating medical devices that are manufactured, repackaged, relabeled, and/or imported to be sold in the United States. Its mission "is to protect and promote the public health. We facilitate medical device innovation by advancing regulatory science, providing industry with predictable, consistent, transparent, and efficient regulatory pathways, and assuring consumer confidence in devices marketed in the U.S."[2] The center's purview includes regulation of *technologies for the heart*, cardiovascular devices that treat a range of diseases that affect the heart.

Most implantable devices to treat heart disease are classified as the highest risk, Class III, because they are life sustaining and/or life supporting. Class III implantable devices include pacemakers, defibrillators, heart valves, coronary stents, ventricular assist devices, and artificial hearts. Manufacturers that wish to market Class III devices in the United States need to demonstrate that there is a reasonable assurance of both *safety* (i.e., the probable benefits to health outweigh any probable risks) and *effectiveness* (i.e., the device will provide clinically significant results).

Comprehensive evaluation of a premarket submission for a therapeutic, high-risk medical device is typically supported by a combination of valid scientific evidence from four types of models: animal, bench, computational, and human. These models can be leveraged at different stages of a medical device's life cycle to demonstrate attributes of performance. Because each model has different strengths and limitations for predicting real-world clinical outcomes, the data portfolio for different devices and use conditions will vary. Some advantages of each model are shown in Table 1.

## Regulatory Evaluation

### *Selecting the Appropriate Model for Evaluation*

A firm that decides to manufacture a medical device should consider the regulatory pathway that will allow the device to be marketed in the United States. For many implantable devices to treat heart disease, a premarket approval (PMA) application is the appropriate pathway; PMA is "the FDA process of scientific and regulatory review to evaluate the safety and effectiveness of Class III medical devices."[3]

The firm must also develop a plan to gather the necessary valid scientific evidence to demonstrate a reasonable assurance of safety and effectiveness. The basis of this plan will depend on the indications for use—the disease to be treated, the affected patient population, the location of the implanted device, the expected duration and in vivo conditions of the implant, and the surgical procedure. With this information, the firm can use tools such as the Device Evaluation Strategy (FDA 2013, section 6.3) and Failure Modes and Effects Analysis (FMEA) for Medical Devices (ISO 2007) to address fundamental questions about device failure and potential consequences (Box 2).

---

[2] Information about the Center for Devices and Radiological Health is available at www.fda.gov/AboutFDA/CentersOffices/OfficeofMedicalProductsandTobacco/CDRH/ucm300639.htm.

[3] Information about the PMA is available at www.fda.gov/Medicaldevices/Deviceregulationandguidance/Howtomarketyourdevice/Premarketsubmissions/Premarketapprovalpma/Default.Htm.

**TABLE 1 Comparison of models used to assess high-risk medical devices**

| | Cost | Time | Ability to vary parameters | Evaluation involving harm | Simplifying assumptions | Relevance to clinical use | Evaluating disease state | Experimental control | Ability to interpret data and predict clinical use |
|---|---|---|---|---|---|---|---|---|---|
| Animal | moderate | moderate | limited | restricted | moderate | species variability | difficult | relatively high | limited |
| Bench | low | short | limited | yes | many and always | limited | simplified states | high | limited |
| Computer | relatively low | short to moderate | high | yes* | many and always | variable | yes* | high | yes* |
| Human | very high | long | not easy | no, unethical | minimal | direct | yes | low | not easy |

* There is a recognized potential. Computational modeling in medical devices, as compared to other industries, is nascent and is the one model with the most potential for refinement and improvement because other models are fairly mature.

Depending on the function of the device, the firm identifies an attribute, the potential failure mode of that attribute, potential device and clinical effects, the design characteristic intended to mitigate the risk of the failure mode, and the model (animal, bench, computational, or human) that will be used to demonstrate that the function of the device will be attained and/or that the failure mode will not likely occur.

In vivo animal studies provide anatomic and clinical pathologic information about local and systemic responses to device use. Larger animal models, such as pigs and sheep, are typically used for cardiovascular applications because the size and response of their anatomy more closely match those of human anatomy. Bench and computational models can act as surrogates for the in vivo environment and are useful because they can challenge an isolated feature of the device (e.g., implant integrity after deployment, long-term durability). Clinical trials are used for a variety of purposes, but for Class III devices they are mainly to demonstrate safety and effectiveness in the clinical setting and evaluate the device in the in vivo human environment.[4]

### *Unique Material Considerations*

When a firm uses traditional materials (e.g., stainless steel, polyurethane), whose behavior is well understood, the regulatory expectations tend to be straightforward. Additional engineering and regulatory questions may arise when complex materials are introduced and their behaviors are not well established. For example, there has been a shift from bare metal stents to drug-eluting and, more recently, absorbable stents.

Questions about drug-eluting stents have focused on understanding the elution and absorption rates of the drug, in addition to the mechanical performance of the stent. With absorbable devices, a major concern is the rate of degradation: absorbable devices are not

[4] For other applications of clinical evaluations see FDA (2013).

**BOX 2**
**Questions from a Failure Modes and Effects Analysis**

- What is the device intended for?
- What could go wrong?
- Why would the failure happen?
- What would be the consequences of failure?
- What is the likelihood of occurrence?
- What is the likelihood of detection?
- What is the severity of the failure mode?

Source: ISO (2007).

intended to be permanent implants like metallic stents, but they do need to maintain a certain amount of structural integrity. Computational methods can be used for stress analysis, but they require more complex constitutive models. Other challenges arise for drug-eluting and absorbable products when the manufacturing process changes, because this can affect the elution and absorption rates for the drug or the degradation time frame for the absorbable material, which could result in additional testing. Identification of byproducts and their biological effects is another common consideration, and can involve complex in vivo (animal model) evaluations.

*Valid scientific evidence from animal, bench, computational, and human models is needed to support a marketing application.*

For medical devices that are tissue-engineered or regenerative medicine products, the regulatory framework is a bit different. Reviewers have to consider "purity, potency, and identity" for biologically derived products,[5] and this requirement can pose limitations to traditional testing. For example, the long-term durability of permanent metallic implants (e.g., stents and heart valve frames) can be evaluated using accelerated durability bench testing and computational modeling, and the resulting data complement the outcomes from the clinical study regarding mechanical performance. This is not the case for tissue- and cell-based materials because the bench model does not allow for the cell and tissue adaptation process that occurs in vivo (e.g., cell infiltration and extracellular matrix deposition) and that may enable the product to repair itself in a normal timed setting in vivo. Therefore, manufacturers of biologic products must rely on extensive in vivo animal testing for performance evaluation.

[5] Information about this requirement is available at www.fda.gov/AboutFDA/CentersOffices/OfficeofMedicalProductsandTobacco/CBER/ucm133072.htm.

### *Changes to Surgical Approaches*

Another aspect of device design that can affect regulatory questions is a change in surgical technique or approach. For example, a recently introduced percutaneous (transcatheter) approach for implanting heart valves for high-risk patients engendered new questions about deliverability, deployment accuracy, migration, integrity, and durability. The latter two are especially important with the new approach and are specifically assessed through a process called *preconditioning*: The heart valve is loaded onto a delivery system and guided through the arterial system, a process that subjects it to stresses and strains that do not occur in the traditional open surgical approach, in which the heart valve is directly implanted in the annulus. Preconditioning can greatly affect the integrity and durability of the implant and determine whether it is suitable for clinical use.

Unlike surgical bioprosthetic heart valves, transcatheter heart valves vary greatly in design, so the effects of preconditioning can be different for each design. Moreover, unlike surgically implanted mechanical heart valves, transcatheter valves do not usually remain circular upon implantation because the diseased leaflets and the calcium nodules are not removed, so the frame experiences noncircular deformations in vivo. The computational model is the only tool that can be used to determine changes in the stress (or strain) state of a device under different preconditioning states or implantation configurations. It can also predict the effects of preconditioning and implantation on fatigue performance (Duraiswamy et al. 2013). These predictions are then confirmed through accelerated durability testing.

### *Summary*

Firms must provide valid scientific evidence from animal, bench, computational, and human models to support their marketing applications, and the amount of data collected from each model depends on the disease to be treated, the affected patient population, the location of the implanted device, the expected duration of the implant, and the surgical procedure. The data portfolio may change even more as companies expand their use of high-performance scientific computing to reduce time and cost in their efforts to bring safe and effective devices to patients in the United States.

## Treatment Planning in the 21st Century

The practice of medicine is being shaped by powerful imaging capabilities, high-performance computation, wireless transmission of data, and massive storage of information. Physicians are now able to continuously monitor a patient's health from a distance and determine whether a coronary lesion is relevant and treatment necessary, whether a patient is at risk of losing heart rhythm, and whether a patient will benefit from cardiac pacing (Miller 2014). In the near future, they will be able to select the optimal heart valve size and placement and to assess treatment options within a matter of hours (Simulia Community News 2014).

Several companies make such options available in the United States. Graphium Health uses cloud computing and mobile technology to help physicians, administrators, and patients make better pre- and postsurgery decisions about care. HeartFlow uses patient-specific anatomy and physiological conditions to computationally estimate the amount of coronary burden due to a stenosis, alleviating in moderate cases the need for catheterization, an invasive procedure that is currently the standard of care.

Thanks to these and other tremendous advances, doctors have access to more data, information, and knowledge, and the potential to offer more clinical benefit to their patients. However, regulators are challenged with trying to determine which advances in computing and software are medical devices and, for those that are, what data are needed to support their entrance to the market in the United States (FDA, FCC, and HIT 2014).

From an engineering perspective, scientific computing is mature enough to simulate multiple design parameters and use conditions, and to visualize complex processes to revolutionize the way medical devices are investigated, treatments planned, and patient data utilized. With access to "digital patients," device designers can download anatomic and physiologic computer models of patients with a given disease.[6] They can then take their new device concepts and "deploy" them in the digital patients to simulate device performance, leading to more effective bench testing, in vivo animal studies, and (actual) clinical trials. The simulations enable detection of "soft failures," failures that occur virtually before the devices are implanted in patients.

Finally, from a clinical perspective, physicians will soon be able to use simulation to predict the safety and effectiveness of a given medical product for an individual patient, thereby truly realizing personalized medicine. However, the regulatory burden for medical devices that have the potential to predict patient-specific outcomes remains to be determined.

*Regulators are challenged with trying to determine which advances in computing and software are medical devices.*

[6] Two such resources are available from the Virtual Physiological Human (www.vph-institute.org) and the Foundation for Research on Information Technologies in Society (IT'IS) (www.itis.ethz.ch/services/anatomical-models).

## Conclusions

New materials and surgical approaches are generating more treatment options for patients with heart disease. Moreover, there is a huge opportunity for imaging and high-performance computing to improve net health outcomes in the United States through treatment planning and better patient understanding of options. FDA's engagement with industry and academia early on in the development of innovative products can help accelerate the field. The agency can provide the structure to help guide firms to determine appropriate models and data portfolio needs for evaluating their products. Early engagement also enables FDA to share its regulatory experience and to raise important questions that will protect patients and promote the overall health of the US population.

## Acknowledgments

The author is grateful for the assistance of numerous contributors: Maureen Dreher, Carmen Gacchina-Johnson, Victor Krauthamer (in developing Box 1), Ken Skodacek, Jeremiah Wille, and Changfu Wu.

## References

Duraiswamy N, Ekrami Y, Weaver J, Retta S, Wu C. 2013. Non-circular configurations increase heart valve leaflet stresses and alter leaflet kinematics: A computational approach. Proceedings of the ASME 2013 Conference on Frontiers in Medical Devices: Applications of Computer Modeling and Simulation, September 11–13, Washington.

FDA [US Food and Drug Administration]. 2013. Investigational Device Exemptions (IDEs) for Early Feasibility Medical Device Clinical Studies, Including Certain First in

Human (FIH) Studies. Center for Biologics Evaluation and Research. Bethesda. Available at www.fda.gov/downloads/medicaldevices/deviceregulationandguidance/guidancedocuments/ucm279103.pdf.

FDA, FCC, and HIT [US Food and Drug Administration, Federal Communications Commission, and Office of the National Coordinator for Health Information Technology]. 2014. FDASIA Health IT Report: Proposed Strategy and Recommendations for a Risk-Based Framework. Available at www.fda.gov/aboutfda/centersoffices/officeofmedicalproductsandtobacco/cdrh/cdrhreports/ucm390588.htm.

Go AS, Mozaffarian D, Roger VL, Benjamin EJ, Berry JD, Blaha MJ, and 41 others. 2014. Heart disease and stroke statistics—2014 update: A report from the American Heart Association. Circulation 129:e28–e292.

Heidenreich PA, Trogdon JG, Khavjou OA, Butler J, Dracup K, and 11 others. 2011. Forecasting the future of cardiovascular disease in the United States: A policy statement from the American Heart Association. Circulation 123:e933–e944.

ISO [International Organization for Standardization]. 2007. 14971:2007 Medical devices—Application of risk management to medical devices. Geneva. Available at www.iso.org/iso/catalogue_detail?csnumber=38193.

Miller K. 2014. Doing the heart good: Translating models to the clinic. Biomedical Computation Review (Spring): 20–28. Available at http://biomedicalcomputationreview.org/content/doing-heart-good-translating-models-clinic.

Murphy SL, Xu JQ, Kochanek KD. 2013. Deaths: Final data for 2010. National Vital Statistics Reports 61(4). Hyattsville, MD: Division of Vital Statistics, Centers for Disease Control and Prevention. Available at www.cdc.gov/nchs/data/nvsr/nvsr61/nvsr61_04.pdf.

Simulia Community News. 2014. Looking deep into heart valve replacement. May, pp. 14–15. Available at http://feops.com/sites/default/files/simulia-scn-1405.pdf.

*Storage and transportation of wastewater from unconventional oil and gas production create challenges in microbial control of the water.*

# Microbial Ecology of Hydraulic Fracturing

Kelvin B. Gregory

Kelvin B. Gregory is an associate professor in the Department of Civil and Environmental Engineering at Carnegie Mellon University.

Advances in drilling and stimulation technologies have greatly improved the economics of oil and gas production from deep, tight, hydrocarbon-rich shale formations. But the unconventional drilling required for this production is associated with challenges in the management of both the wastewater that is coproduced at the surface and the microbial communities in this water.

The focus of this article is on the microbial ecology and biogeochemical processes that impact the production of oil and gas, management of wastewater (both flowback and produced water), and product quality from hydraulically fractured wells. Hydraulic fracturing is discussed from the perspective of water management, including the volume and makeup of fracturing fluids that give rise to produced water microbiology. Recent studies of the chemistry and microbiology of produced water from the Marcellus and Barnett shale regions are discussed. Microbial ecology present at wellheads is described as well as that of stratified impoundments for produced water. The concluding section considers the implications of microbial control for unconventional production and identifies research needed to address them.

## Hydraulic Fracturing Overview

Horizontal drilling, a technology that has been broadly applied since the 1980s, allows access to a far greater portion of a formation than vertical wells by following the horizontal contour of the formation for thousands of meters. In this manner, horizontal wells also greatly reduce surface impacts by minimizing the number of wells required to develop a particular area. Hydraulic fracturing (often called *fracking*) is used in conjunction with horizontal wells to increase the permeability of a formation and extend the radius of influence of the wellbore for an overall increase in the productive area of the reservoir.

Hydraulic fracturing entails the pumping of fluid into the wellbore at a rate that exceeds the capacity of the formation to accept without fracturing. A number of fracturing fluids exist, the most common of which is a mix of water (as a solvent for chemical modifiers), sand (for proppant), and chemicals. This fluid is pumped into the wellbore at pressures of 500–900 atm, depending on the needs of the target formation. The proppant flows into preexisting and newly initiated fractures and holds them open after pumping has stopped and pressure decreases. In the Marcellus shale region, hydraulic fracturing may require 6–15 million liters of water, depending on the depth to the target formation and length of the horizontal leg of the well (Gregory et al. 2011).

*A wide variety of organic compounds in produced water contribute to bacterial growth.*

## Flowback and Produced Water

### *Generation of Fluid*

After the pumping for hydraulic fracturing but before the production of hydrocarbons, the pressure in the well is allowed to dissipate; fluid returns to the surface through the wellhead and is collected and stored. This initial fluid, which is produced to the surface for about 14 days before product recovery, is called *flowback*. Thereafter, water produced to the surface (along with hydrocarbon products) over the lifetime of the well is called *produced water*. The difference between flowback and produced water is largely operational; the rate at which flowback returns to the surface is greater and the strength lower than that of produced water.

In terms of content, both flowback and produced water are a mixture of hydraulic fracturing fluid and water present in the formation. The quantity and quality of flowback vary among unconventional oil and gas plays and according to the hydraulic fracturing procedure used. In the Marcellus shale, for example, flowback returns 9–53 percent (average 10 percent) of the injected volume (Vidic et al. 2013). In terms of the quality of the fluid, the concentration of total dissolved solids (TDS, including salts and metals) in the water that returns to the surface varies over time; the earliest flowback (e.g., the first 2 days) resembles the hydraulic fracturing fluid itself and has the lowest concentration of TDS, while the later flowback (e.g., after day 10) and the produced water have much higher TDS, more like the chemistry of the formation water.

Generally speaking, the composition of produced water from a formation is similarly variable (Barbot et al. 2013). The study by Barbot and colleagues reveals that the TDS in produced water from the Marcellus varied from ~1 to 345 g/L, with an average of 106 g/L. The authors also found that the TDS in the produced water was predominantly from the ions ($Cl^-$, $Na^+$, and $Ca^{2+}$) and further characterized by high concentrations of magnesium, barium, and strontium. Organic compounds in produced water include those introduced with the fracturing fluid as well as polycyclic aromatic hydrocarbons (PAHs), heterocyclic compounds, alkyl phenols, aromatic amines, alkyl aromatics (alkyl benzenes, alkyl biphenyls), long-chain fatty acids, and aliphatic hydrocarbons (Orem et al. 2014), all of which may be used as carbon sources and electron donors for bacterial growth.

### *Disposition of Fluid*

Most produced water in the United States is disposed through deep-well injection (Clark and Veil 2009). However, because there are few deep-well injection options in Pennsylvania, reuse of flowback as the makeup water for subsequent hydraulic fracturing has become the preferred management option in the Marcellus region. This reuse also reduces both the need for freshwater withdrawals and the costs incurred for transportation and treatment or disposal. Produced water brines are used for subsequent hydraulic fracturing, diluted with a freshwater source, and treated to remove solids and divalent cations before reuse. Although the reuse of flowback (and produced) water for hydraulic fracturing is a novel technology and management solution for oil and gas wastewater brines, a recent analysis of data from the Pennsylvania Department of Environmental

Protection revealed a ~90 percent reuse rate of oil and gas brines from the Marcellus (Maloney and Yoxtheimer 2012).

Flowback is typically impounded at the surface before disposal, treatment, or reuse. While treatment or disposal may take place immediately, reuse for subsequent fracturing requires storage of a variable volume of wastewater (from 10,000 to 60,000 m$^3$, depending on the intended use and the number of wells served) for variable periods of time (weeks or months); for this it is either transported by truck or pumped to centralized impoundments that serve multiple wells or multiple pads with multiple wells.

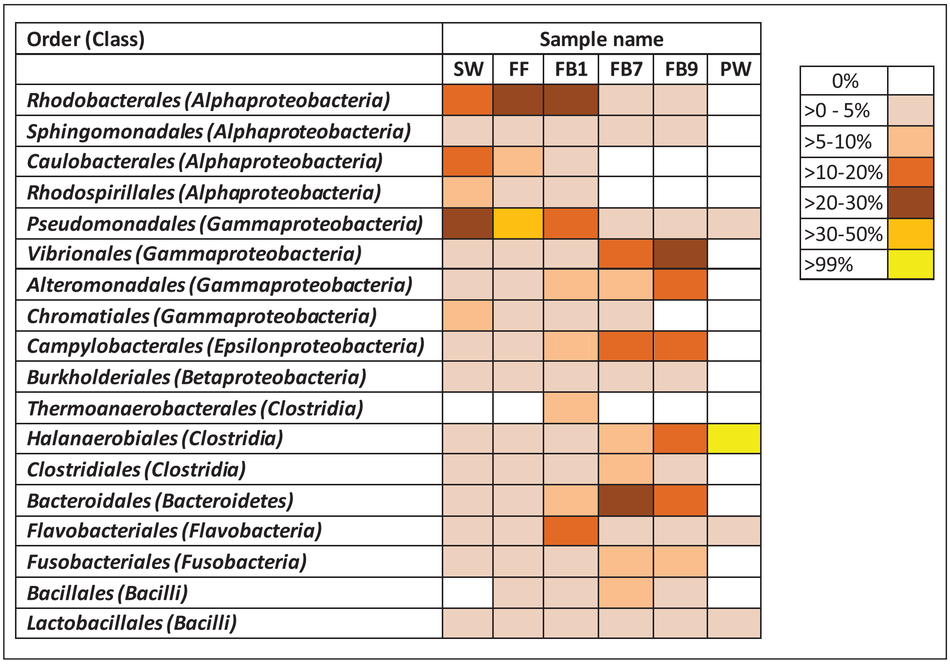



FIGURE 1 Heat map revealing the relative abundance of bacterial taxa in water samples associated with hydraulic fracturing of the Marcellus Shale as revealed by 454 pyrosequencing. FF = fracturing fluid; FB1, 7, 9 = flowback on days 1, 7, 9; PW = produced water on day 187; SW = source water.

In storage, microbes in the flowback and produced fluids evolve and give rise to water management challenges such as malodorous compounds, biofouling of the formation and production equipment and infrastructure, biocorrosion, and alteration of the solubility of metals including radionuclides. Issues associated with the proliferation of bacteria during oil and gas production are ubiquitous, manifest themselves throughout the production infrastructure, and are costly to manage (Ollivier and Magot 2005).

## Microbial Communities in Produced Fluids

Microbial processes that impact oil production from conventionally developed reservoirs are well documented (Van Hamme et al. 2003). In these reservoirs, the stimulation of bacteria may result in reservoir fouling, biocorrosion, and product souring (sulfidization), or, conversely, provide benefit by enhancing product recovery and the removal of soured product and paraffins. The microbial ecology of these processes in conventional reservoirs is well understood, but there are few studies of the detrimental or beneficial impacts of bacteria or the microbial ecology of unconventional oil and gas development, despite similar concerns and knowledge that the microbiology is costly to control.

### *From Aerobic to Anaerobic Bacteria*

A recent study of wellhead samples of Marcellus flowback and produced water reveals that the microbial community changes over time together with the geochemistry (Murali Mohan et al. 2013b). On day 1 of the flowback the community closely resembles that of the fracturing fluid and the source water (Figure 1). The microbes are most similar to species associated with nonhalophilic, aerobic, and phototrophic metabolisms, all of which would be expected in water from a freshwater surface source. However, later in the flowback period, the TDS increase as do the number of bacterial species that are most closely related to halophilic, thermophilic anaerobes. The rise in the abundance of halophilic anaerobes occurs at the expense of the nonhalophilic aerobes and phototrophs and at the expense of microbial diversity (Murali Mohan et al. 2013b).

Figure 1 shows a gradual decrease in *Rhodobacterales* (freshwater phototrophs) and increase in *Halanaerobiales* (anaerobic halophiles) during hydraulic fracturing of a well in the Marcellus shale. The emergence of the halophiles was concomitant with the emergence of anaerobic geochemistry (e.g., $Fe^{2+}$ and $HS^{-}$) in the water and led to the loss of virtually all species present in the initial flowback except the *Halanaerobiales*, which eventually represented more than 99 percent of the community (Cluff et al. 2014). Bacteria identified in a sample of produced water were closely associated anaerobic, fermentative, and sulfur-reducing bacteria in the *Halanaerobiales*. A study of flowback from the Barnett shale revealed a community that was similarly changing with time, adapting to anoxic and saline conditions (Struchtemeyer and Elshahed 2011).

### *Possible Sources of Bacteria*

It is important to note that next generation sequencing revealed that the anaerobic and halophilic species present in great abundance in the produced water were also present in very low abundance in hydraulic fracturing fluid. This suggests that the organisms in the produced water may originate at the surface and be introduced by hydraulic fracturing rather than native to the connate water in the deep subsurface reservoir. But there is a chicken and egg problem: trucks and equipment used for handling the water likely were exposed to brines from hydraulic fracturing, so the source of the organisms could be any equipment used for hauling the water. It is therefore difficult to pinpoint the source of the organisms in flowback and produced water.

*Organisms in the produced water may originate at the surface and be introduced by hydraulic fracturing.*

Although bacteria are well known to inhabit deep subsurface environments (Fredrickson and Balkwill 2006), their presence in connate brine from the Marcellus and Barnett formations has not been documented. Obtaining representative samples that are assured to be free of bacterial contamination from drilling or sampling is difficult and costly as the source formations are in extremely low permeability rock. Any bacteria that were present when the formation sealed were at temperatures and pressures sufficient to produce natural gas from biosolids—more than 120°C for millions of years. With those temperatures, durations, and limited permeability for nutrient delivery, the rapidly evolving robust microbial communities in wellhead samples are not likely. However, shallow and lower-temperature hydrocarbon-rich formations and those that contain natural fractures (which may serve as pathways for the exchange of fluids, as in the Antrim basin in Michigan) are more likely to have a native community (Martini et al. 1998).

Regardless of the source of organisms at the wellhead, they come in contact with equipment for handling and transporting fluids and eventually are in an impoundment where new geochemistry, impacted by management strategy and the surface environment, drives further changes in these adaptive bacterial communities.

## Microbial Communities in Impoundments

Impoundments for storage of flowback and produced water have robust and dynamic microbial communities that correspond to the geochemistry of the impoundment water. Impoundments receive water and bacteria from a variety of sources, including wells, source water, drilling fluids (Struchtemeyer et al. 2011), equipment, and the environment (e.g., rain, dust, animals, runoff). Which species are capable of surviving depends on their ability to adapt to brine concentrations above 100 g/L and to the spatially and temporally dynamic geochemistry that results from environmental processes and human intervention during impoundment management.

The only study of the microbiology in flowback water impoundments finds that such microbial communities stratify with the impoundment chemistry and are impacted by management strategy (Murali Mohan et al. 2013a). The onset of anaerobic conditions in an impoundment may be detected by malodorous compounds from bacterial activity associated with volatile fermentation products and sulfide gas; this aesthetic issue is commonly controlled by the addition of biocides or aeration of the impoundment.

Samples collected at depths ranging from the surface to the bottom of aerated and unaerated impoundments revealed that the geochemistry and microbiology in the aerated impoundment were homogeneous throughout (Figure 2). Moreover, findings show that the microbial community at all depths contained species that were most similar to known aerobes and phototrophs. This follows from the expected vertical mixing of the community between the bottom and surface depths from vigorous aeration. In contrast, the untreated impoundment was geochemically and microbially stratified: bacteria that were most similar to aerobes and phototrophs were confined to the surface layer and anaerobes (such as sulfidogenic and methanogenic bacteria) were confined to the anoxic middle and bottom layers. In all samples, regardless of treatment or depth, the species present were most similar to taxa that are known halophiles, showing that the brine conditions of the water are an overarching driver of the ecology.

The study does not reveal the activity of the organisms, but it does suggest that the bacteria in impoundments adapt to the conditions imposed, despite the addition of biocides to the initial fracturing water (Murali Mohan et al. 2013a), as reported from studies of flowback from the Barnett shale as well (Struchtemeyer and Elshahed 2011).

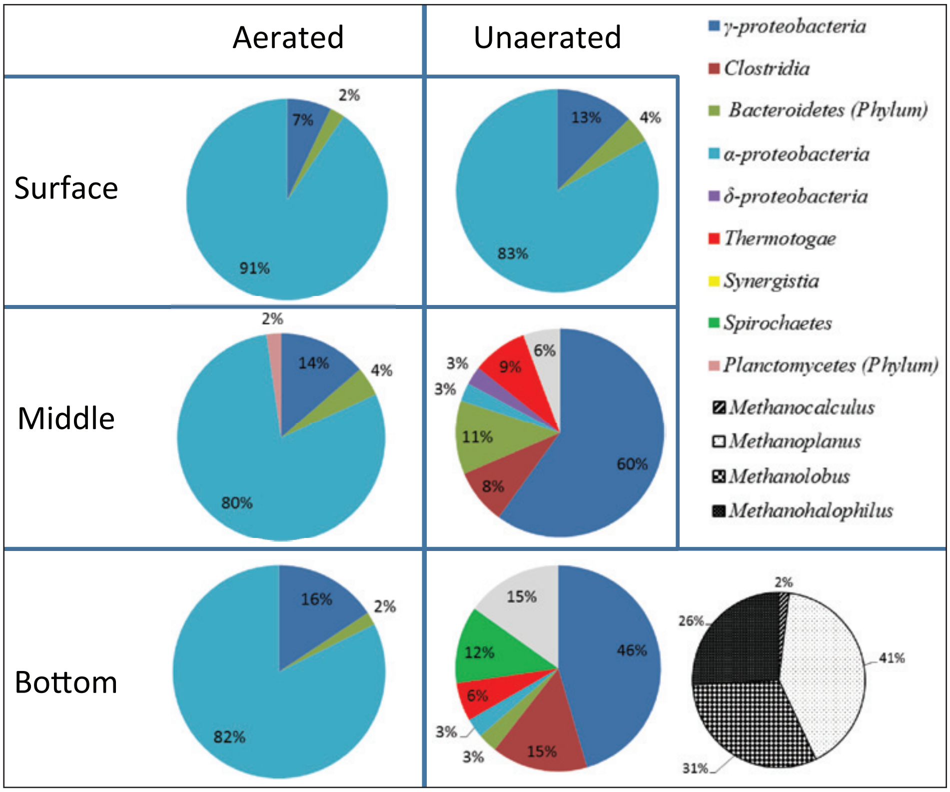



FIGURE 2 Relative abundance of bacterial taxa in flowback water impoundments at various depths. Data generated by clone libraries and subsequent sequencing of 16s rRNA genes recovered from samples. Sequences with similarity to Archaea were recovered only from the bottom of the unaerated impoundment and are shown in black and white. Data adapted from Murali Mohan et al. (2013a).

## Implications for Unconventional Oil and Gas Production

Research into the microbiology of unconventional oil and gas development is a nascent focus area for engineers and scientists. There are some similarities with conventional petroleum microbiology, but many research questions remain about water management associated with unconventional development. Their answers will affect the practice as well as the economic and environmental sustainability of hydraulic fracturing for oil and gas production.

Most importantly, studies to date indicate that the microbial communities present in wellheads and impoundments appear to be dynamic in time and space, indicating that biocides may not be working or used as intended. Moreover, microbial diversity drops sharply during flowback as it becomes enriched with survivor species. The implication is that recycling of flowback and produced water for subsequent hydraulic fracturing may introduce to new wells deleterious bacteria that are adapted to the harsh environment of the well (and biocides). These bacteria grow quickly, advance the onset of sulfide production, and are more resistant to treatment options.

Studies have also shown the presence and abundance of species that are similar to *Halanaerobium congolense*, a sulfidogen. Sulfide production in wells is associated with human and environmental health risks, corrosion, and costly degradation of product quality. This organism has been identified in produced waters from conventional development, but is of significance here because it cannot reduce sulfate and instead uses thiosulfate and sulfur as electron acceptors for sulfide production. Because standardized tests for assessing sulfidogenic potential in produced water rely on the numbers of sulfate-reducing bacteria, they will yield false negative reports for sulfide production potential, a risk for the industry. New tests that enable assessment of sulfide production from sulfur-reducing bacteria are needed for unconventional wells.

## References

Barbot E, Vidic NS, Gregory KB, Vidic RD. 2013. Spatial and temporal correlation of water quality parameters of produced waters from Devonian-Age shale following hydraulic fracturing. Environmental Science and Technology 47:2562–2569.

Clark CE, Veil JA. 2009. Produced Water Volumes and Management Practices in the United States. ANL/EVS/R–09/1. Environmental Science Division, Argonne National Laboratory.

Cluff MA, Harsock A, MacRae JD, Carter K, Mouser PJ. 2014. Temporal changes in microbial ecology and geochemistry in produced water from hydraulically fractured Marcellus shale gas wells. Environmental Science and Technology 48:6508–6517.

Fredrickson JK, Balkwill DL. 2006. Geomicrobial processes and biodiversity in the deep terrestrial subsurface. Geomicrobiology Journal 23:345–356.

Gregory KB, Vidic RD, Dzombak DA. 2011. Water management challenges in development of shale gas with hydraulic fracturing. Elements 7:181–186.

Maloney KO, Yoxtheimer DA. 2012. Production and disposal of waste materials from gas and oil extraction from the Marcellus shale play in Pennsylvania. Environmental Practices 14:278–287.

Martini AM, Walter LM, Budai JM, Ku TCW, Kaiser CJ, Schoell M. 1998. Genetic and temporal relations between formation waters and biogenic methane: Upper Devonian Antrim Shale, Michigan Basin, USA. Geochimica et Cosmochimica Acta 62:1699–1720.

Murali Mohan A, Hartsock A, Hammack RW, Vidic RW, Gregory KB. 2013a. Microbial communities in flowback water impoundments from hydraulic fracturing for recovery of shale gas. FEMS Microbial Ecology 86:567–580.

Murali Mohan A, Hartsock A, Bibby KJ, Hammack RW, Vidic RW, Gregory KB. 2013b. Microbial community changes in hydraulic fracturing fluids and produced water from shale gas extraction. Environmental Science and Technology 47:13141–13150.

Ollivier B, Magot M. 2005. Petroleum Microbiology. Washington: ASM Press.

Orem W, Tatu C, Varonka M, Lerch H, Bates A, Engle M, Crosby L, McIntosh J. 2014. Organic substances in produced and formation water from unconventional natural gas extraction in coal and shale. International Journal of Coal Geology 126:20–31.

Struchtemeyer CG, Elshahed MS. 2011. Bacterial communities associated with hydraulic fracturing fluids in thermogenic natural gas wells in North Central Texas, USA. FEMS Microbial Ecology 81:13–25.

Struchtemeyer CG, Davis JP, Elshahed MS. 2011. Influence of the drilling mud formulation process on the bacterial communities in thermogenic natural gas wells of the Barnett Shale. Applied and Environmental Microbiology 77:4744–4753.

Van Hamme JD, Sing A, Ward OP. 2003. Recent advances in petroleum microbiology. Molecular and Microbiology Reviews 67:503–549.

Vidic RD, Brantley SL, Vandenbossche JM, Yoxtheimer D, Abad JD. 2013. Impact of shale gas development on regional water quality. Science 340:1235009.

# An Interview with . . .

## Henry Petroski

Henry Petroski (NAE) is a professor of both civil engineering and history at Duke University and a prolific author. Photo by Catherine Petroski.

**Ron Latanision (RML):** Henry, we are very pleased that you are willing to talk with us. Let me briefly explain how this all came about. Last year Cameron and I were thinking that we needed to add a new dimension to the *Bridge*. Engineers have an impact in all sorts of ways in our culture, not only in terms of building bridges and developing new iPhones and the like. We thought it would be a good idea to look at what kinds of involvement engineers have had in the culture of the United States and the world.

We began the series with an interview with Richard Blanco, a poet who is also a civil engineer. We learned that there are politicians who are engineers and that led us to John Sununu. Hopefully, you will be followed by Charley Johnson, a former NFL quarterback. We are now very glad to have an engineer who not only teaches engineering but also is a well-known writer. We are delighted that you are available to talk with us today.

**Henry Petroski (HP):** I am honored. I have read the first two interviews.

**RML:** That is great. As with the others, we're going to record this conversation, transcribe it, and send it for you to review. Does that sound all right?

**HP:** That sounds fine.

**Cameron Fletcher (CHF):** It'll be a fairly short turnaround; is there any reason that might not be feasible for you?

**HP:** Not over the next three weeks.

**RML:** What happens in three weeks, Henry? I am just curious.

**HP:** My editor is visiting this weekend and I expect that I am going to have a deadline.

**CHF:** What is your new book?

**HP:** I am taking a historical look at American infrastructure, all aspects of it—the usual, the condition of roads, potholes; I also go into some unusual details—where did lane markings come from, why are they the colors they are. It turns out that this was a very important stage in the organization and control of traffic. Early roads had no markings at all on them. There were a lot of accidents, especially going around blind curves; putting a centerline down the road turned out to be an enormous benefit to road safety. But then for decades, literally, there were debates about whether the lines should be white or yellow. I trace things like that, and where the traffic light came from. Then I get into current politics, or rather policy: How are we going to pay for the infrastructure? Where do we get the money? Do we increase the gas tax? And so forth.

The timing of this book is going to be pretty touchy because these are developing issues. One of the things my editor and I have to talk about is exactly when this book is going to be published so I can aim for some kind of closure on the issues.

**CHF:** Infrastructure is a hot topic these days. Are you considering other aspects besides transportation?

**HP:** Principally, I am doing roads and bridges because that is what I know the most. That alone is more than a book can handle, it turns out. I do touch on other aspects of infrastructure, but I don't go into any depth about them. I want to keep this book focused, and I think spreading it out over all of infrastructure wouldn't make for a very coherent book.

I do have one chapter where I talk about the American Society of Civil Engineers and its report cards issued every three years or so. They cover the whole spectrum of infrastructure in the United States, so in that chapter I get away from the focus on transportation, but then I bring the discussion back to roads and bridges to talk about infrastructure issues in a more focused way.

**RML:** You mentioned in passing the politics of the issue. On both sides of the aisle in Congress, there is agreement that the infrastructure and particularly bridges and roads in the United States need to be improved but disagreement on how to pay for it.

**HP:** That is exactly right. But neither side wants to give the other side an advantage politically. The president's federal budget was just released—in fact, it has a bridge on the cover. I guess that shows how important the subject is to the politicians in Washington.

**RML:** I hope in your book you might somehow encourage policymakers to think rationally about the fact that, if infrastructure is so fundamental to our standard of life and commerce and other aspects of our culture, we really need to take care of it and come together and figure out how to pay for it.

*I think engineers should think more about politics and public policy.*

**HP:** I certainly agree with you. I also think engineers, at least in my experience, should think more about politics and public policy. I have had arguments with some of my colleagues, not necessarily my current ones, about whether they really were expressing their opinions enough about what is right and wrong with regard to significant infrastructure policies. Some of them have told me they did not think that was their place. They thought they were the technical people and that was it. I think that is disappointing.

We certainly try to teach our students that, as engineers, there are important public policy issues that they are very close to and are expert in technically, and that gives them additional insight into where policy should go.

**CHF:** What do you think is a good way to encourage your colleagues and peers to expand their view of themselves to the policy sphere?

**HP:** I guess try to catch them as students before they get indoctrinated the other way. For some reason, whether it is early education or the environment in which they grow up, they have this mindset. That has been my experience. Some think that they should be involved in everything, others think they should be involved in nothing. I think it has a lot to do with personality, with personal confidence about whether you have the self-assuredness of being correct in your conclusions. I do not think a lot of engineering education conveys to engineering students these ideas.

I have been getting a little experience with first-year students at the university. It is becoming clear over the years that they are becoming further and further removed from current events. These are not just engineers, I am talking about across the curriculum because I teach a freshman seminar in which I have students that are engineers and nonengineers alike. I have learned that I can't just make a reference to something that is happening. The students do not read the newspaper, they do not seem to follow the news, politics generally. They are not acting like engaged citizens.

When I was in school (I guess I am showing my age when I say things like that) we used to take courses in citizenship, where we learned about the organization of government and what the citizen's responsibility was—not only to vote, but to know the issues. Your expertise was a contribution to the exercise of government in some way.

**RML:** Kids now use social media far more than they read the newspapers.

**HP:** I have always thought of the local newspaper as a collection of social media. I read our local newspaper every day. It has a lot of letters to the editor, it is a public forum and there is a lot of local news. I cannot imagine something being closer to the real issues of the neighborhood. Students today just don't read papers. But then, when I was young, neither did I do so closely. I had a newspaper route; I folded the papers every day, but I didn't really read them. I would read the headlines only because they were staring at me. I wrote a memoir about this. Before writing that book, I went back and read the papers I had delivered and was amazed at what I had missed.

**CHF:** Looking at the range of topics you have covered in your books, it seems to me you could have pursued a host of interests. What prompted you to choose engineering as your platform from which to explore all these topics?

**HP:** I think the honest answer is that engineering found me. It was precipitated by Sputnik. I was beginning to think about college and majors and so forth when Sputnik went up in 1957. Afterward, there was a very conscious effort in the country to encourage students to go into engineering and science and math so we could go beat the Soviets.

It is not unlike the emphasis today on the STEM curriculum—science, technology, engineering, and math—although I don't think that what's happening today is quite as focused. In the Sputnik era there were fellowships and scholarships given out to encourage students to study engineering and science. I guess there were probably a lot of research grants that went to faculty at that time, but that was outside my knowledge. Today, it seems like a lot of the money is going to curriculum as opposed to students.

**RML:** I, too, am a product of that era. I think there was a great deal of fear on the part of the American public and the government, and that was a tremendous incentive and motivation to produce more scientists and engineers so that we could keep pace with the Soviets. I think we both were beneficiaries of that in lots of ways.

I am curious about your teaching and your research and then your transition to writing. You are a civil engineer—

**HP:** I am in a civil engineering department and I have the title of professor of civil engineering, but my degrees are in mechanical engineering and mechanics, theoretical and applied mechanics in particular. Mechanics historically has been taught in the civil engineering department at Duke, so when I was hired here to teach mechanics I ended up in the civil engineering department. In fact, I didn't know much about civil engineering at all when I was appointed. I took it upon myself to really study it, almost as if I were a student again, because I wanted to be able to communicate with my colleagues and of course with the students who were studying civil engineering.

That got me interested in a lot of things that I continue to have a deep interest in, like bridges and infrastructure. I have been always very grateful for the opportunity to do so. It was sort of an accident, but it has worked out very well.

With regard to how I ended up in engineering: When I was going to college I had a circle of friends, and we used to talk a lot, usually over a beer down at the local place. There weren't standardized tests in engineering per se; they were in science and math and vocabulary and language skills and so forth. We would ask ourselves, If we are so good in science and math, how come we are studying engineering? Why aren't we studying science and math? We became rather introspective about this stuff. I never changed my major to science or math, but I did vacillate between civil and mechanical engineering and changed my major. I think I went back and forth a couple of times.

*Today, it seems like a lot of the money is going to curriculum as opposed to students.*

I ended up in mechanical engineering largely because I had a fairly bad experience working for the New York City Traffic Department one summer among a lot of civil engineers who were just not inspiring, let's put it that way. They watched the clock and the thermometer because there was a rule that if the temperature got to a certain degree, the work day was over. I still learned a lot working for them, I got out in the field a little bit. It was very interesting.

I would say my friends and I had a very liberal education even though we were majoring in engineering. We took courses in philosophy, economics, literature, history—I enjoyed every course I took, except maybe thermodynamics. Everything was interesting. Whatever was thrown at us we just soaked it up.

**CHF:** It sounds like you are advocating more of a liberal arts or humanities education.

**HP:** I wouldn't go that far. We had to take a lot more credit hours, and so we had plenty of room in the curriculum back then. This was before computers pretty much. I feel that my education was well rounded. As a result, no subject really scared me off. You were asking before about the range of things I write about. I don't know if I would go so far as to say nothing intimidates me, but I don't say I can't deal with something because I don't know anything about it. I didn't know anything about engineering before I studied it. You study something and you learn something.

*A neighbor asked me, What is engineering? I could not give a concise answer in lay terms, and that got me thinking.*

**RML:** I bet you didn't take a course in etiquette, Henry, did you? I did as an undergraduate.

**HP:** I did have "charm school" in graduate school. It was not a formal course. I was a teaching assistant, and anybody teaching a course for the first time had to go to charm school, including professors. This was at the University of Illinois, Urbana-Champaign. It was expected that you would wear a jacket and tie to teach. We would have to demonstrate what our lecture was going to be for the coming week and we had to have the proper demeanor to teach. It was all taken very seriously.

The jacket and tie didn't bother me too much because I wore them all through high school, I was used to that. But the idea of practicing and auditioning your lectures, that was something new. Just teaching was something new. I still to this day don't know how I taught my first class because I didn't feel comfortable in front of audiences at the time.

**RML:** You taught at the University of Illinois and at Texas…

**HP:** That's right. I went to the University of Illinois as a graduate student. I received a fellowship, then they also offered me an opportunity to teach, first as a teaching fellow and later I became a teaching assistant to support myself because my professor did not have any research grants at the time. I taught just about every year I was a graduate student. I ended up with the rank of instructor while I was still a graduate student. Then I went to the University of Texas at Austin for my first teaching job as an assistant professor. When I interviewed for the job, it was in the Department of Engineering Mechanics. When I arrived, I was informed that I was now in the Department of Aerospace Engineering and Engineering Mechanics. I did not expect that. I taught there for about five years.

That's when I transitioned to writing. I had three degrees in engineering, I had practiced engineering, and I was a registered professional engineer (while I was at Texas, the legislature passed a law defining teaching as practicing engineering, so if you were teaching engineering you were supposed to be registered). However, when one of my neighbors asked me, What is engineering? I could not give a concise answer in lay terms. This got me thinking about what is engineering. I wasn't sure I fully understood it. In all these courses I had taken and taught, in all of this education, that is never talked about. I guess it is sort of a meta-subject or something like that. I started thinking about it.

I had been writing since I was an undergraduate, when I had to do some writing for some of my literature courses, one in particular. The teacher encouraged me and I found that I enjoyed doing it. I continued to do what I would call recreational writing through graduate school and even while I was a young assistant professor. Mostly poetry actually, a lot of it published.

Then I began to be attracted to prose. I'm not sure I can reconstruct right here how that transition occurred. I began to write what I would call parodies or satires on public affairs, public policy relating to engineering and science, energy bills in Congress, budget bills, and so forth. I began to publish these in the *New York Times*; I didn't have a regular column or anything, but I think it was a fair number of pieces.

I found that prose was more satisfying than poetry mainly because it had a bigger audience; not too many people actually read poetry. I began to write longer pieces and eventually ended up writing fairly regularly for *Technology Review*, the MIT magazine. At first I was writing op-ed pieces, opinion pieces, point of view pieces, but more serious than what I was writing for the *Times*. The editor encouraged me to write some longer pieces, feature articles in particular, and I enjoyed doing it.

I began writing expository pieces about engineering.

One that I wrote was about failure. It was one of my first ones because I had gotten interested in failure. This was around the time the Hyatt Regency's walkway collapsed [Kansas City, 1981]. The editor asked me, Why don't you write a little sidebar on that because it's current news? I did, and enjoyed doing that because I was able to explain what happened in nontechnical terms.

Eventually, all this comes together. I never thought I could write a book because it was just too daunting while I'm teaching and supposed to have a research program and everything. The poetry worked fine because I could do that late at night before I went to bed, but longer stuff I really had to devote some time to.

**RML:** It required some research.

**HP:** Research and dedicated time and so forth. What is engineering? I still was searching for that answer. Because I had learned that writing about something helped me think about it, I decided I was going to write a book on the topic. Actually, Samuel Florman's *Existential Pleasures of Engineering* (1976) was not only influential but actually encouraging. I did not know Sam at the time. Reading his book—and noting the fact that it was reviewed in the *New Yorker*—reinforced the idea that a book was a way of talking about engineering to a much broader audience, clearly not a technical audience alone. That was what I was aspiring to back then.

One summer I disciplined myself to write for a couple of hours each morning before going to my office. I ended up with a book manuscript. That is where I discovered what I think engineering is. It ended up being all about failure and avoiding failure. The short definition of engineering is the avoidance of failure, design to obviate failure, or however you want to put it.

**CHF:** What was that book title?

**HP:** *To Engineer Is Human* (1985). The subtitle is *The Role of Failure in Successful Design*.

**RML:** You mentioned Sam Florman. I am going to quote from a recent message he sent me; he said, "If I ever form a society of engineer writers, Henry will have to be the emperor. Nobody else comes close." You have one very large fan in Sam Florman, himself a very good writer.

I am curious about a day in the life of Henry Petroski. How do you put into your schedule teaching and research and writing? With something like 18 books, and maybe number 19 is in the works now, you must have a good system for managing your time to get all this done. How do you do that? As an academic, you have a responsibility for teaching and research, and at the same time you are a very prolific writer.

**CHF:** Are you still writing two hours every morning?

**HP:** Yes, I write every morning if I can. If I am traveling, I don't always do it. I tend to read when I am traveling.

I guess I am very lucky today. My institution, the administrators, my dean, they all seem to see my value as a writer about engineering and related things. They give me a lot of leeway. I don't sit and talk to them about this because as long as they leave me alone, I leave them alone.

I remember when one of my books came out, I think it was *The Pencil* (1990), I was on "The Today Show" to promote it. Shortly after that, I was in a meeting—I forget the details of what the meeting was about, but it was people from across campus, and the president of the university was there. I had to get up and leave early because I had to teach. As I was leaving, the president said "Henry, congratulations on being on 'The Today Show' the other day. That was wonderful exposure for Duke" or something to that effect. He was clearly approving of what I was doing. Coming from the president, that endorsed it to everybody in earshot. Since then, it has been a comfortable relationship I have with the institution.

*The short definition of engineering is the avoidance of failure, design to obviate failure.*

**RML:** I think that is entirely appropriate. I mentioned at the outset that one of our goals with this column is to demonstrate that engineers affect the culture of this country. The books you've written can be read by a very broad audience. They emphasize engineering, but they also emphasize familiar experiences, not just in terms of pencils and paper clips and so on but also, for example, the most recent one that I've seen, *The House with Sixteen Handmade Doors* (2014). You touch on things that are in the experience of anyone who might pick up the book. That is a contribution in terms of the culture of the country. I really enjoy reading them.

**HP:** Thanks. I'm pleased to know that.

**CHF:** What kinds of feedback do you get from readers, particularly those who are not engineers?

**HP:** It ranges all over the place. Just the other day I got an email from some guy who teaches creative writing and he's working on a novel, if I get this right, taking place in the 18th century. He is asking me if they still used paper knives back then. There was a time when book pages were not fully cut and you had to use what was called a paper knife to cut them before you proceeded to read. He was trying to be correct technically and not anachronistic in referring to these pages. That kind of stuff comes out of the blue.

**RML:** What is the answer to that question, Henry?

*I was sitting in my study one evening, thinking, What am I going to write about next? I looked at the bookshelves and saw them as little bridges.*

**HP:** I had to punt a little because I didn't want to stop and do any research. I happened not to address paper knives explicitly in my book on books and bookshelves. I told him that I do remember reading books from the library in my own experience that were published in the 20th century that still had pages uncut and were clearly published that way. The question was, When did they start getting cut? I told him in this book I wrote, *The Book on the Bookshelf* (2000), there are two illustrations that span two centuries. In one of them, the books are being sold unbound; the printer would fold but not cut the pages, the binder would. That was a demarcation point. Exactly when did that happen? Probably over a rather long period of time because, just like today, certain publishers do things a little differently than other publishers. Not everybody is going to do it the same way all of a sudden. That is just a recent example.

**RML:** What is next in terms of the kinds of writing you do? Do you have novels anywhere in the inventory of things you would like to write?

**HP:** I have thought about fiction, but have never really gone very far with the idea. I don't read an awful lot of fiction these days. When I was a student, I did, especially Russian literature, in translation of course. But today I hardly read anything that isn't related to what I am working on at the time. I read fiction if it is about an engineer or about engineering or some kind of related topic. But as a rule, I don't read fiction.

I really admire a good plot. I admire how an author will put together a story, but I don't know that I've got it in me. I have enough on my plate right now. I have no immediate plans.

**CHF:** What fiction have you read about engineers? My curiosity is piqued.

**HP:** There is a book called *No Highway* (1948) by Nevil Shute, about an aeronautical engineer. It was made into a movie titled *No Highway in the Sky* (1951) starring Jimmy Stewart. This guy works in the airplane industry, and certain types of planes start exploding. Ron, you no doubt know the de Havilland Comet story; the novel really is about the Comet. The hero is tracking down what was responsible for the lost planes. It turns out to have been metal fatigue. The book is very explicitly about engineering throughout.

And Sam Florman has written a "novel of survival" titled *The Aftermath* (2001), in which several hundred engineers attending a conference on a ship sailing off the southeast coast of Africa are among the few survivors of a comet's impacting the other side of the Earth. The engineers, along with a surviving agricultural community, set themselves the task of rebuilding civilization.

**CHF:** How do you decide what topics to pursue for each book?

**HP:** Something that interests me or catches my interest. For *The Book on the Bookshelf* I was sitting in my study one evening, thinking, What am I going to write about next? and I looked at the wall of books, the bookshelves. Usually you see books when you do that, but I saw the shelves that day. I saw them as little bridges. Why is it that we store books this way? That was the germ of the idea. There was enough interest there for me to pursue the idea. I didn't think there necessarily was a book on it, but then I began to read—it was very interesting research, full of surprises. It turned out to be a pretty successful book. I get a lot of questions about the topics in that book.

And then another criterion is, Is there enough material to fill a book? Is there going to be an engaging story? I like to think of the books as telling a story of some kind, though maybe not a novelistic type of story. As long as it is engaging to me, I hope it will be engaging to others. I have abandoned a lot of ideas because they did not seem to go anywhere, but some just cry out to be pursued. With *The Pencil*, for example, early on in trying to feel my way around this subject I discovered that Henry David Thoreau had manufactured pencils and was innovative in helping his father in his pencil business, which was a cottage industry in Concord, Massachusetts. I knew that that alone made it a promising book. The question was, What else was going to be in the book? It turns out that the Thoreau business is a chapter in the book, and I open with an anecdote about Henry David. But once there was that connection to the general culture I began to think, What about the materials, what about the graphite of a pencil, what about the wood? It turns out to be very interesting—whether the graphite is pure or not, whether the wood has the right properties. This turned it into a book about engineering.

*The Pencil* has a very interesting story. I wanted to take a sabbatical and for that you have to have a project. I usually don't know much about my books when I begin them, but in this case I had to know more if I was going to say I would like to write this book. I had to explain it. My first idea was that this was going to be a book about engineering and culture. My idea was to use a pencil as an introduction to a lot of different concepts—the pencil is clearly associated with creativity, with artists and architects and engineers. I would have a chapter where I would start off talking about the pencil as this tool of creativity, and I would get into how engineers are creative. That was the germ of the idea. My working title was "With a Pencil" and that is what I applied for fellowships with.

But I seldom think through the books that far. Usually after I finish a book or at least a good draft of one, *then* I make an outline and submit to a publisher. I cannot make an outline of a book beforehand because I deviate too much from my original ideas. It depends on where the material is going to take the subject.

**RML:** Your books are a perfect marriage of engineering and history. I can see why you have a joint appointment in civil engineering and in history. You are looking at engineering objects and at the same time tracing their history and considering cultural implications.

**HP:** Thank you.

**RML:** We promised we wouldn't take more than an hour. One last question, Henry, and that is whether there is any comment or message you would like to deliver to the other members of the NAE who will be reading this column.

---

*I cannot make an outline of a book beforehand because it depends on where the material takes the subject.*

---

**HP:** I don't want to presume to send a message to them. I really am so honored to be a member of the NAE, given the distinguished people that are members. I was blown away when I was elected and invited to sit on committees. I got to know some of the members and was just so overwhelmed and impressed with the variety of qualities they would bring to a discussion—their intelligence, knowledge, integrity, the depth of analysis they would engage in to make decisions about awards and other matters. I have never been involved with a group that has so impressed me. I hope I can live up to the standards that have been set by the members of the Academy.

**RML:** I think that is a given, Henry, I really do. This column focuses on how practicing engineers affect the culture of the country and you are a perfect model of that. I am just delighted that we have had this opportunity to spend an hour with you. Thanks again, Henry, very much.

**CHF:** Yes, indeed, Henry, thank you. What a pleasure.

**HP:** It has been good to talk with you, Ron and Cameron.

# NAE News and Notes

## Class of 2015 Elected

In February 67 new members and 12 foreign members were elected to the National Academy of Engineering, bringing the total US membership to 2,263 and the number of foreign members to 221.

Academy membership honors those who have made outstanding contributions to "engineering research, practice, or education, including, where appropriate, significant contributions to the engineering literature," and to the "pioneering of new and developing fields of technology, making major advancements in traditional fields of engineering, or developing/implementing innovative approaches to engineering education."

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

**Harry A. Atwater Jr.,** Howard Hughes Professor of Applied Physics and Materials Science, California Institute of Technology, Pasadena. For contributions to plasmonics.

**Hari Balakrishnan,** professor of computer science, Massachusetts Institute of Technology, Cambridge. For contributions to wired and wireless networks and distributed systems.

**Ewa A. Bardasz,** president, ZUAL Associates Consulting, Mentor, Ohio. For novel automotive lubricants, low-emission engine development, and education of engineering professionals.

**Sangeeta Bhatia,** investigator, Howard Hughes Medical Institute; John J. and Dorothy Wilson Professor of Health Sciences and Technology and Electrical Engineering and Computer Science, Massachusetts Institute of Technology; and director, Laboratory for Multiscale Regenerative Technologies, Cambridge, Massachusetts. For tissue engineering and tissue regeneration technologies, stem cell differentiation, and preclinical drug evaluation.

**Cheryl A. Blanchard,** chief executive officer, MicroCHIPS Inc., Lexington, Massachusetts; and consultant, Blanchard Consulting LLC, Fort Wayne, Indiana. For creation and commercialization of biomaterial products and gender-based medical devices for musculoskeletal health.

**Kevin G. Bowcutt,** senior technical fellow and chief scientist of hypersonic design and applications, Boeing Co., Huntington Beach, California. For development and demonstration of air-breathing hypersonic vehicles and implementation of design optimization methods.

**Jonathan D. Bray,** faculty chair in earthquake engineering excellence and professor of geotechnical engineering, University of California, Berkeley. For contributions to earthquake engineering and advances in mitigation of surface faulting, liquefaction, and seismic slope failure.

**Emery N. Brown,** Warren M. Zapol Professor of Anaesthesia, Harvard Medical School; Edward Hood Taplin Professor of Medical Engineering and professor of computational neuroscience, Massachusetts Institute of Technology, Cambridge. For development of neural signal processing algorithms for understanding memory encoding and modeling of brain states of anesthesia.

**Wesley G. Bush,** chair, chief executive officer, and president, Northrop Grumman Corp., Falls Church, Virginia. For engineering leadership in national security.

**Jonathan P. Caulkins,** H. Guyford Stever Professorship of Operations Research and Public Policy, Carnegie Mellon University, Pittsburgh. For contributions to the analysis, modeling, and engineering of drug policy in the United States and abroad.

**Anantha Chandrakasan,** Joseph F. and Nancy P. Keithley Professor of Electrical Engineering and head, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge. For development of low-power circuit and system design methods.

**Santosh K. Das,** retired vice president, Polymer Technologies Inc., Randolph, New Jersey. For understanding of the composition, structure, property, and processing interrelationships of rapidly solidified amorphous and microcrystalline alloys.

**Ingrid Daubechies,** professor and James B. Duke Professor of Mathematics, Duke University, Durham, North Carolina. For contributions to the mathematics and applications of wavelets.

**Deepakraj M. Divan,** president, chief technical officer, and cofounder, Varentec Inc., San Jose, California. For design and commercialization of advanced power conversion technologies for improved quality and controllability of the power grid.

**Derek Elsworth,** professor of energy and geoenvironmental engineering, Pennsylvania State University, University Park. For contributions to understanding natural processes affecting flow and transport properties of fractured rocks.

**Eric D. Evans,** director, MIT Lincoln Laboratory, Lexington. For development of remote sensing systems, improvised explosive device (IED) detection, and ship antimissile defense.

**Raymond J. Fonck,** Steenbock Professor of Physical Science and professor of engineering physics, University of Wisconsin, Madison. For advances in fusion plasma spectroscopy diagnostics and leadership of the US fusion program into the burning plasma era.

**Tahir Ghani,** Intel Senior Fellow, technology and manufacturing group, and director, transistor technology and integration, Intel Corp., Hillsboro, Oregon. For development of transistor technologies for logic products.

**Morteza (Mory) Gharib,** vice provost for research, Hans W. Liepmann Professor of Aeronautics, and professor of bioinspired engineering, California Institute of Technology, Pasadena. For contributions to fluid flow diagnostics and imagery, and engineering of bioinspired devices and phenomena.

**Bernd Girod,** Robert L. and Audrey S. Hancock Professor of Electrical Engineering; senior associate dean, online learning and professional development; and faculty director, Center for Image Systems Engineering, Stanford University, California. For contributions to video compression, streaming, and multimedia systems.

**Karen Klincewicz Gleason,** associate provost and Alexander and I. Michael Kasser Professor of Chemical Engineering, Massachusetts Institute of Technology, Cambridge. For invention, application development, scale-up, and commercialization of chemically vapor-deposited polymers.

**Dan M. Goebel,** senior research scientist, Jet Propulsion Laboratory, California Institute of Technology, Pasadena. For contributions to low-temperature plasma sources for thin-film manufacturing, plasma materials interactions, and electric propulsion.

**Robert H. Grubbs,** Victor and Elizabeth Atkins Professor of Chemistry, California Institute of Technology, Pasadena. For developments in catalysts that have enabled commercial products.

**Supratik Guha,** director of physical sciences, Thomas J. Watson Research Center, IBM Corp., Yorktown Heights, New York. For contributions to field effect transistor technology that allow continued scaling of silicon microelectronics.

**Ronald Hamburger,** senior principal, Simpson Gumpertz & Heger Inc., San Francisco. For advances in seismic design principles and practices for buildings through research and development of codes and guidelines.

**Robert E. Henry,** emeritus senior vice president and Regent Consultant, Fauske & Associates LLC, Burr Ridge, Illinois. For understanding and analysis of severe power reactor accidents and their impact on design and accident management.

**Janet G. Hering,** director, Swiss Federal Institute of Aquatic Science and Technology, Dübendorf; and professor, Swiss Federal Institutes of Technology, Lausanne and Zürich. For contributions to understanding and practice of removal of inorganic contaminants from drinking water.

**J. Jim Hsieh,** chair and chief executive officer, Sheaumann Laser Inc. (formerly Axcel Photonics Inc.), Marlborough, Massachusetts. For development and commercialization of long-wavelength lasers for fiber-optic communication.

**Ming Hsieh,** chair, chief executive officer, and cofounder, Fulgent Therapeutics, Temple City, California. For development and commercialization of biometric identification systems.

**S. Jack Hu,** interim vice president for research, J. Reid and Polly Anderson Professor of Manufacturing Technology, professor of mechanical engineering, and professor of industrial and operations engineering, University of Michigan, Ann Arbor. For methods for predicting and diagnosing root causes of product quality variation in multistage assembly systems.

**Thomas M. Jahns,** Grainger Professor of Power Electronics and Electrical Machines, and professor of electrical and computer engineering, University of Wisconsin, Madison. For advancement of permanent magnet machines and drives for transportation and industrial applications.

**Milan M. Jovanovic,** vice president of research and development, Delta Products Corp., Research Triangle Park, North Carolina. For efficiency improvements of AC-DC power supplies in information technology systems.

**Robert L. Kleinberg,** Schlumberger Fellow, Schlumberger-Doll Research, Cambridge, Massachusetts. For contributions to formation evaluation and development of pulsed nuclear magnetic resonance logging.

**John Klier,** distinguished fellow and global research and development director, polyurethanes and automotive systems, Dow Chemical Co., Midland, Michigan. For contributions to novel coatings, polymer dispersions, and low volatile organic compounds technologies.

**Leonard F. Konikow,** scientist emeritus, US Geological Survey, Reston, Virginia. For modeling of coupled groundwater and surface water flow and of solute transport in groundwater.

**Ellen J. Kullman,** chair and chief executive officer, E.I. du Pont de Nemours and Co., Wilmington, Delaware. For leadership in the business growth and transformation of a global science and engineering company.

**Philip Li-Fan Liu**, Class of 1912 Professor in Engineering, and director of the School of Civil and Environmental Engineering, Cornell University, Ithaca, New York. For coastal engineering research, education, computer modeling, and leadership for tsunami and wave damage.

**Nils Lonberg,** senior vice president, immuno-oncology and biologics discovery, Bristol-Myers Squibb, Redwood City, California. For development of fully human monoclonal antibody therapeutics using innovative transgenic expression systems.

**Brian McClendon,** vice president of engineering, Google Inc., Mountain View, California. For strategic, technical, and managerial leadership resulting in widespread accurate and useful geographic information.

**Samir Mitragotri,** director, Center for Bioengineering, and professor of chemical engineering, University of California, Santa Barbara. For development, clinical translation, and commercialization of transdermal drug delivery systems.

**George Kenneth Muellner,** vice chairman of the board, the Aerospace Corp., El Segundo, California. For leadership in the research, design, and development of advanced air and space vehicles.

**Kyle J. Myers,** director, division of imaging and applied mathematics, Center for Devices and Radiological Health, US Food and Drug Administration, Silver Spring, Maryland. For development of analytical and regulatory science methods for accuracy and safety of medical imaging devices.

**Radia Perlman**, Fellow, EMC Corporation, Hopkinton, Massachusetts. For contributions to Internet routing and bridging protocols.

**Dana Auburn Powers,** senior scientist, nuclear energy and fuel cycle programs, Sandia National Laboratories, Albuquerque. For contributions to commercial nuclear power plant safety worldwide and to radioactive source-term processes.

**Clayton J. Radke,** professor of chemical engineering, University of California, Berkeley. For understanding of mixed-wettability and foam-enhanced oil recovery through thin film and pore-scale models.

**Guruswami Ravichandran,** John E. Goode Jr. Professor of Aerospace, professor of mechanical engineering, and director, Graduate Aerospace Laboratories, California Institute of Technology, Pasadena. For contributions to mechanics of dynamic deformation, damage, and failure of engineering materials.

**Junuthula N. Reddy,** distinguished professor, Regents' Professor, and inaugural holder of the Oscar S. Wyatt Jr. Endowed Chair in Mechanical Engineering, Texas A&M University, College Station. For contributions to composite structures and to engineering education and practice.

**L. Rafael Reif,** president, Massachusetts Institute of Technology, Cambridge. For technical and educational contributions and for university leadership.

**Virginia M. Rometty,** chair, president, and chief executive officer, IBM Corp., Armonk, New York. For strategic applications of systems engineering and leadership in development of services science and its application to business processes.

**Daniela Rus,** Andrew (1956) and Erna Viterbi Professor of Electrical Engineering and Computer Science and director, Computer Science and Artificial Intelligence Laboratory, Massachusetts Institute of Technology, Cambridge. For contributions to distributed robotic systems.

**David J. Srolovitz,** Joseph Bordogna Professor of Engineering and Applied Science, University of Pennsylvania, Philadelphia. For theory and simulation of microstructure and properties of materials and leadership in computational materials engineering.

**Graeme L. Stephens,** director, Center for Climate Sciences, Jet Propulsion Laboratory, California Institute of Technology, Pasadena. For elucidation of Earth's cloud system and radiation balance.

**Virginia C. Sulzberger,** retired director of engineering, North American Electric Reliability Corp., Livingston, New Jersey. For leadership and development of electric power system reliability standards.

**Richard Szeliski,** distinguished scientist, Microsoft Corp., Redmond, Washington. For contributions to computer vision, computer graphics, and interactive image and video rendering.

**Gabor C. Temes,** professor, Electrical Engineering and Computer Science Department, Oregon State University, Corvallis. For contributions to analog signal processing and engineering education.

**Doros N. Theodorou,** professor of chemical engineering, National Technical University of Athens, Greece. For statistical-mechanical-based strategies and simulation algorithms to predict the structure and properties of polymers and zeolites.

**Michael J. Todd,** Leon C. Welch Professor, School of Operations Research and Information Engineering, Cornell University, Ithaca, New York. For contributions to the theory and application of algorithms for continuous optimization.

**Gavin P. Towler,** vice president and chief technology officer, UOP LLC (a Honeywell company), Des Plaines, Illinois. For process designs for commercial petrochemicals and for leadership in refining and chemical research.

**Michael Tsapatsis,** professor and Amundson Chair in Chemical Engineering and Materials Science, University of Minnesota, Minneapolis. For design and synthesis of zeolite-based materials for selective separation and reaction.

**Harry L. Van Trees,** professor emeritus and director emeritus, Center of Excellence in Command, Control, Communications, Computing, and Intelligence, George Mason University, Fairfax, Virginia. For contributions to detection, estimation, and modulation theory and leadership of defense communication systems.

**Norman J. Wagner,** Robert L. Pigford Chair of Chemical Engineering, College of Engineering, and joint professor, Department of Physics and Astronomy, University of Delaware, Newark. For understanding flow-induced microstructural transitions in complex liquids and invention of ballistic-resistant fabrics by strain-hardening suspensions.

**Mark R. Wiesner,** James L. Meriam Professor of Civil and Environmental Engineering, and director, Center for the Environmental Implications of Nanotechnology, Duke University, Durham, North Carolina. For contributions to membrane technologies for water treatment and understanding of environmental behavior and risk of nanomaterials.

**Eric F. Wood,** Susan Dod Brown Professor of Civil and Environmental Engineering, Princeton University, New Jersey. For development of land surface models and use of remote sensing for hydrologic modeling and prediction.

**James J. Wynne,** program manager, local education outreach, Thomas J. Watson Research Center, IBM Corp., Yorktown Heights, New York. For co-invention of excimer laser surgery for vision corrective procedures.

**Vigor Yang,** William R.T. Oakes Professor and chair, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta. For contributions to combustion physics in propulsion systems and to aerospace engineering education.

**David D. Yao,** Piyasombatkul Family Professor and professor of industrial engineering and operations research, Columbia University, New York City. For understanding of stochastic systems and their applications in engineering and service operations.

**Ajit P. Yoganathan,** Regents' Professor, Wallace H. Coulter Distinguished Faculty Chair in Biomedical Engineering, and director, Center for Innovative Cardiovascular Technologies, Georgia Institute of Technology, Atlanta. For improvements in the biomechanics of prosthetic heart valves and the development of heart repair devices.

## New Foreign Members

**Patrick Couvreur,** professor and director, Physical Chemistry, Pharmaceutical Technology, and Biopharmacy Laboratory, University of Paris-Sud (Paris-XI), Châtenay-Malabry, France. For advances in nanomedicine and commercialization of targeted nanotechnology systems for cancer treatment.

**R. Allan Freeze,** president, R. Allan Freeze Engineering Inc., White Rock, British Columbia, Canada. For numerical modeling, stochastic subsurface hydrology, risk assessment, and optimization for groundwater engineering.

**Lynn F. Gladden,** pro-vice-chancellor for research and Shell Professor of Chemical Engineering, University of Cambridge, United Kingdom. For contributions to chemical reactor engineering through the uniquely specific application of magnetic resonance imaging.

**Graeme John Jameson,** Laureate Professor of Chemical Engineering and director, Centre for Multiphase Processes, University of Newcastle, New South Wales, Australia. For development of innovative flotation technology for advanced mineral processing.

**Amable Liñán,** professor emeritus, motor propulsion and thermal fluid dynamics, School of Aeronautical Engineering, Polytechnic University of Madrid, Spain. For discoveries using asymptotic analyses in combustion and for contributions to advance engineering science.

**Nelson Martins,** assistant to the director general and research consultant, electrical power systems, CEPEL, Brazilian Electrical Energy Research Center, Rio de Janeiro. For development of dynamic analysis software tools and techniques for large electric power systems.

**Masayoshi Nakashima,** professor, Disaster Prevention Research Institute, Kyoto University, Japan. For large-scale dynamic testing of buildings that has advanced structural earthquake engineering.

**David A. Nethercot,** emeritus professor of civil engineering, Imperial College London, United Kingdom. For contributions to structural steel design and construction, and for service to structural engineering worldwide.

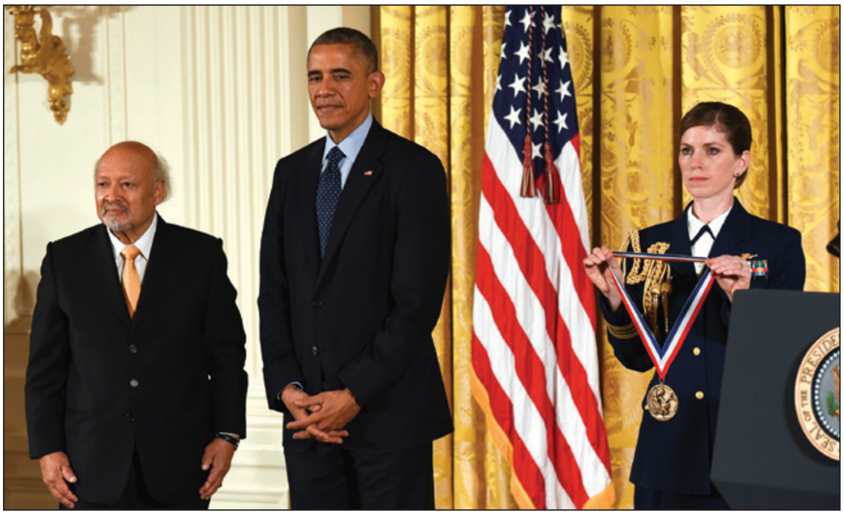
**Jens Kehlet Nørskov,** Leland T. Edwards Professor of Engineering, professor of photon science, and director, SUNCAT Center for Interface Science and Catalysis, Stanford University, California. For theoretical approaches to design of heterogeneous catalysts, linking reaction rates to microscopic catalyst properties.

**Ghavam Shahidi,** IBM Fellow and director of silicon technology, Thomas J. Watson Research Center, IBM Corp., Yorktown Heights, New York. For contributions to silicon-on-insulator complementary metal-oxide semiconductor (CMOS) technology.

**M.C.M. (Mark) van Loosdrecht,** professor and group leader, environmental biotechnology, Delft University of Technology, Den Haag, Netherlands. For the invention and development of wastewater treatment systems for nutrient removal.

**Martin Vetterli,** professor, communication systems, Ecole Polytechnique Fédérale de Lausanne, Switzerland. For development of time-frequency representations and algorithms in multimedia signal processing and communications.

## NAE Members Receive One National Medal of Science and Four National Medals of Technology and Innovation



Thomas Kailath, National Medal of Science Laureate.

The 2012 National Medal of Science Laureates and 2012 National Medal of Technology and Innovation Laureates received their medals from President Obama on November 20, 2014, at a White House ceremony. The medals are the nation's highest honors for achievement and leadership in advancing the fields of science and technology. In announcing the laureates, President Obama said, "These scholars and innovators have expanded our understanding of the world, made invaluable contributions to their fields, and helped improve countless lives. Our nation has been enriched by their achievements and by all the scientists and technologists across America dedicated to discovery, inquiry, and invention." Five NAE members were among the recipients of these prestigious awards.

NAE member **Thomas Kailath**, Hitachi America Professor of Engineering Emeritus, Stanford University, received the National Medal of Science "for transformative contributions to the fields of information and system science, for distinctive and sustained mentoring of young scholars, and for translation of scientific ideas into entrepreneurial ventures that have had a significant impact on industry."

The National Medal of Technology and Innovation, which recognizes those who have made lasting contributions to America's competitiveness and quality of life and helped strengthen the nation's technological workforce, was awarded to four NAE members.

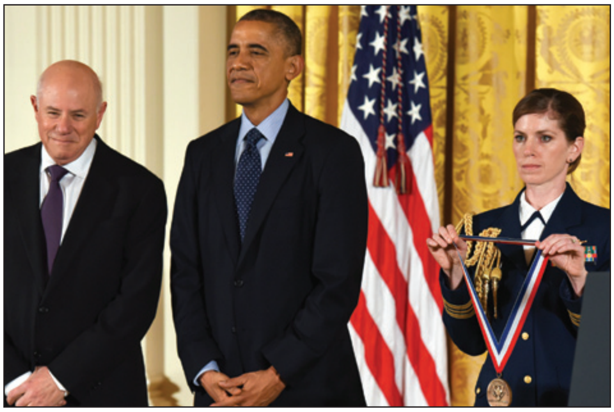
**Edith M. Flanigen**, retired fellow and chemist, UOP LLC, received the award "for innovations in the fields of silicate chemistry, the chemistry of zeolites, and molecular sieve materials."

**Thomas J. Fogarty**, chair, director, and founder, Fogarty Institute for Innovation, was cited "for innovations in minimally invasive medical devices."

**Eli Harari**, founder, retired chair, and CEO, SanDisk Corporation, was recognized "for invention and commercialization of flash storage technology to enable ubiquitous data in consumer electronics, mobile computing, and enterprise storage."

**Cherry A. Murray**, dean, Harvard University School of Engineering and Applied Sciences, was honored "for contributions to the advancement of devices telecommunications and the use of light for studying matter, and for leadership in the development of the science, technology, engineering, and math (STEM) workforce in the United States."

Edith M. Flanigen, National Medal of Technology and Innovation Laureate.



Eli Harari, National Medal of Technology and Innovation Laureate.

Thomas J. Fogarty, National Medal of Technology and Innovation Laureate.

Cherry A. Murray, National Medal of Technology and Innovation Laureate. Photos courtesy of the National Science and Technology Medals Foundation.

# NAE Newsmakers

The Optical Society (OSA) and the IEEE Photonics Society announced that **Paul Daniel Dapkus**, W.M. Keck Distinguished Professor of Engineering at the University of Southern California, is the recipient of the **2015 John Tyndall Award**, one of the most prestigious recognitions in the field of optics. Dapkus was selected for his "pioneering and sustained contributions to the development of metal organic chemical vapor deposition and high performance quantum well semiconductor lasers." The award recognizes an individual who has made pioneering, highly significant, or continuing technical or leadership contributions to fiber-optics technology.

On November 24, 2014, President Barack Obama presented the **Presidential Medal of Freedom** to **Mildred S. Dresselhaus**, Institute Professor of Electrical Engineering and Physics, Massachusetts Institute of Technology, at a White House ceremony.

**Robert S. Langer**, David H. Koch Institute Professor at the Massachusetts Institute of Technology, has been awarded the **2015 Queen Elizabeth Prize for Engineering** for his revolutionary advances and leadership in engineering at the interface with chemistry and medicine. He was the first person to engineer polymers to control the delivery of large molecular weight drugs for the treatment of diseases such as cancer and mental illness. The prize is a £1 million award that celebrates engineers responsible for a groundbreaking innovation of global benefit to humanity.

West Virginia University has established the **Syd and Felicia Peng Professorship in Mining Engineering**, named for **Syd Peng**, Charles E. Lawall Chair Emeritus. Peng hopes the named professorship will "help attract and retain prominent scholars and/or promising scholars who will continue to develop the department to a higher level."

The Prince Sultan bin Abdulaziz International Prize for Water was instituted to encourage scientists and researchers to make contributions to international efforts to preserve water resources. The prize has five categories. In a colorful ceremony in Riyadh, Saudi Arabia, on December 15, 2014, **William W-G. Yeh**, Richard G. Newman AECOM Distinguished Professor of Civil Engineering, University of California, Los Angeles, was awarded the **Water Management and Protection Prize** "for developing optimization models to plan, manage and operate large-scale water resources systems throughout the world."

The 27th International Mineral Processing Congress honored **Roe-Hoan Yoon**, University Distinguished Professor, Virginia Tech, with its **2014 Lifetime Achievement Award**. Yoon was selected for his decades of work in fine particle recovery and associated environmental benefits; his award lecture at the conference in Santiago was titled "From Science to Design of Flotation Circuit Design."

The American Institute of Chemical Engineers (AIChE) presented its most prestigious awards honoring eminent chemical engineers for career accomplishments, service to society, and service to the Institute at the 2014 Annual Meeting Honors Ceremony in Atlanta on November 16. The **Warren K. Lewis Award** recognizing contributions to chemical engineering education was awarded to **L. Gary Leal**, Schlinger Professor of Chemical Engineering, University of California, Santa Barbara, "for outstanding scholarship and academic leadership." The **William H. Walker Award** recognizing excellence in contributions to chemical engineering literature was awarded to **Gregory Stephanopoulos**, W.H. Dow Professor of Chemical Engineering, Massachusetts Institute of Technology, "for advancing the fundamental chemical engineering science supporting metabolic engineering as an enabling technology for the production of pharmaceutical and chemical products from renewable resources." The **Award for Service to Society**, recognizing outstanding contributions by a chemical engineer to community service and to the solution of socially oriented problems, was awarded to **Adam Heller**, research professor, University of Texas at Austin, "for life contributions of medical products that have helped hundreds of thousands of patients suffering from diabetes and other diseases." The **Founders Award for Outstanding Contributions to the Field of Chemical Engineering** is presented to engineers who have had a profound impact on the way chemical engineering is practiced and whose achievements have advanced the profession in any of its aspects. **Stuart Cooper**, professor and chair of the Department of Chemical and Biomolecular Engineering at the Ohio State University, received the award "for innovative research, influential publications, strong administrative leadership, effective mentoring of students and faculty, and outstanding professional service." The **MAC Eminent Chemical Engineers Award** was presented to **Babatunde A. Ogunnaike**, William L. Friend Chaired Professor and dean, College of Engineering, University of Delaware. **Edward L. Cussler**, Distinguished Institute Professor, University of Minnesota, was awarded the **Institute Lecturer Award**. **Kristi S. Anseth**, Distinguished Professor and Howard Hughes Medical Institute Investigator, University of Colorado Boulder, received the **Food, Pharmaceutical, and Bioengineering Division Award in Chemical Engineering**. **Antonios G. Mikos**, Louis Calder Professor of Bioengineering, Rice University, was honored as an **AIChE Fellow**. AIChE also presented the newly renamed **Andreas Acrivos Award for Professional Progress in Chemical Engineering**, which recognizes significant contribution to the science of chemical engineering through theoretical discoveries, the development of new processes, products, or inventions, and other forms of distinguished service.

On June 16, 2014, at the annual conference of the American Society of Engineering Education, **Pablo G. Debenedetti**, Class of 1950 Professor in Engineering and Applied Science, professor of chemical and biological engineering, and dean for research at Princeton University, received the **Benjamin Garver Lamme Award**. It was presented in recognition of his fundamental contributions to modern engineering thermodynamics/statistical mechanics, notably to the understanding of the liquid state, the thermodynamics of super-cooled and glassy water, and the theory of hydrophobicity; and for a broad range of engineering applications of these fundamental advances. He also was honored for his inspired authorship of groundbreaking articles and a landmark textbook, for his talent in and commitment to education and mentorship, and for his dedicated and multifaceted administrative service to his department, engineering school, university, and profession in ways that have profoundly shaped the education and careers of his students and peers. Also at the conference, **John White**, chancellor emeritus and Distinguished Professor of Industrial Engineering at the University of Arkansas, received the **National Engineering Economy Teaching Excellence Award**, in recognition of his accomplishments as a scholar, administrator, and teacher. During his distinguished 50-year career, he coauthored three engineering economy textbooks and taught over 4,000 students, both nationally and internationally.

Election to **National Academy of Inventors (NAI) Fellow** status is a high professional distinction accorded to academic inventors who have demonstrated a highly prolific spirit of innovation in creating or facilitating outstanding inventions that have made a tangible impact on quality of life, economic development, and the welfare of society. They are named inventors on US patents and were nominated by their peers for outstanding contributions to innovation in areas such as patents and licensing, innovative discovery and technology, significant impact on society, and support and enhancement of innovation. NAI Fellows will be inducted on March 20, 2015, as part of the 4th Annual Conference of the National Academy of Inventors at the California Institute of Technology in Pasadena. Fellows will be presented with a special trophy, newly designed medal, and rosette pin in honor of their outstanding accomplishments. NAE members selected for induction are **Ilhan A. Aksay**, professor of chemical and biological engineering, Princeton University; **Jan P. Allebach**, Hewlett-Packard Distinguished Professor of Electrical and Computer Engineering, Purdue University; **Frances H. Arnold**, Dick and Barbara Dickinson Professor of Chemical Engineering, California Institute of Technology; **Nadine N. Aubry**, dean of engineering, Northeastern University; **Joseph J. Beaman Jr.**, professor of mechanical engineering, University of Texas at Austin; **Robert A. Brown**, president, Boston University; **A. Robert Calderbank**, professor of computer science, electrical engineering, and mathematics, Duke University; **James J. Coleman**, Distinguished Chair, Erik Jonsson School of Engineering and Computer Science, University of Texas at Dallas; **Harold G. Craighead**, Charles W. Lake Jr. Professor of Engineering, Cornell University; **Mark E. Dean**, research chair, University of Tennessee, Knoxville; **Russell D. Dupuis**, professor of electrical and computer engineering and Steve W. Chaddick Endowed Chair in Electro-Optics, Georgia Institute of Technology; **Elazer R. Edelman**, Thomas D. and Virginia W. Cabot Professor of Health Sciences and Technology, Massachusetts Institute of Technology; **J. Gary Eden**, Gilmore Family Professor of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign; **Stephen R. Forrest**, professor of electrical engineering &

computer science, physics, and materials science & engineering, University of Michigan; **Elsa Garmire**, Sydney E. Junkins 1887 Professor of Engineering, Dartmouth College; **Maurice P. Herlihy**, professor of computer science, Brown University; **Jeffrey A. Hubbell**, Barry L. McLean Professor for Molecular Engineering Innovation and Enterprise, University of Chicago; **Trevor O. Jones**, president and CEO, International Development Corporation; **Jay D. Keasling**, Hubbard Howe Jr. Distinguished Professor of Biochemical Engineering, University of California, Berkeley; **Juan C. Lasheras**, Stanford and Beverly Penner Professor of Applied Sciences, University of California, San Diego; **Asad M. Madni**, retired president, chief operating officer, and CTO, BEI Technologies Inc.; **Carver A. Mead**, Gordon and Betty Moore Professor of Engineering and Applied Science, Emeritus, California Institute of Technology; **Antonios G. Mikos**, Louis Calder Professor of Bioengineering and Chemical and Biomolecular Engineering, Rice University; **Jan D. Miller**, Ivor Thomas Distinguished Professor of Metallurgy, University of Utah; **Richard K. Miller**, president and professor of mechanical engineering, Franklin W. Olin College of Engineering; **Brij M. Moudgil**, Distinguished Professor of Materials Science and Engineering, University of Florida; **Jose M.F. Moura**, Philip L. and Marsha Dowd University Professor, Carnegie Mellon University; **Shuji Nakamura**, professor of materials and of electrical and computer engineering, University of California, Santa Barbara; **Shree Nayar**, T.C. Chang Professor of Computer Science, Columbia University; **Babatunde A. Ogunnaike**, William L. Friend Chaired Professor and dean, University of Delaware; **Nicholas A. Peppas**, Fletcher Stuckey Pratt Chair in Engineering, University of Texas at Austin; **Victor L. Poirier**, professor, Institute for Advanced Discovery and Innovation, University of South Florida; **Rebecca R. Richards-Kortum**, Stanley C. Moore Professor of Bioengineering, Rice University; **B. Don Russell Jr.**, Distinguished Professor, Regents Professor, and Harry E. Bovay Endowed Chair Professor, Department of Electrical and Computer Engineering, Texas A&M University; **Marwan A. Simaan**, Florida 21st Century Chair and Distinguished Professor of Electrical Engineering and Computer Science, University of Central Florida; **Gordana Vunjak-Novakovic**, Mikati Foundation Professor of Biomedical Engineering and professor of medical sciences, Columbia University.

The **National Inventors Hall of Fame**, which celebrates the life-changing achievements of US patent holders, welcomed three NAE members on May 21, 2014: **Frances H. Arnold**, Dick and Barbara Dickinson Professor of Chemical Engineering, California Institute of Technology; **Mildred S. Dresselhaus**, Institute Professor of Electrical Engineering and Physics, Massachusetts Institute of Technology; and **Ashok J. Gadgil**, director and faculty senior scientist, EETD, University of California Lawrence Berkeley Laboratory.

Four NAE members have been elected **International Fellows of the Royal Academy of Engineering**: **William F. Baker**, partner, Skidmore, Owings & Merrill LLP; **Thomas D. O'Rourke**, Thomas R. Briggs Professor of Engineering, Cornell University; **Richard F. Rashid**, chief research officer, Applications and Services Group, Microsoft Corporation; and **Andrew J. Viterbi**, Presidential Chair Professor, University of Southern California, and cofounder, Qualcomm.

## 2014 EU-US Frontiers of Engineering Hosted by Boeing in Seattle

On November 10–12, 2014, the fourth EU-US Frontiers of Engineering symposium was hosted by the Boeing Company at the Fairmont Olympic Hotel in Seattle. NAE partnered with the European Council of Applied Sciences, Technologies, and Engineering (Euro-CASE) to carry out the event with organizational support for the EU side provided by the National Academy of Technologies of France (NATF). NAE member **Christodoulos Floudas**, Stephen C. Macaleer '63 Professor in Engineering and Applied Science in the Department of Chemical Engineering at Princeton University, served as US cochair; Dr. Yves Caseau, head of the Digital Agency of the AXA Group, was cochair for the EU side.

The meeting brought together approximately 60 engineers, ages 30–45, from US and European universities, companies, and government labs for a 2½-day meeting to discuss leading-edge developments

EU-US FOE participants toured Boeing's Everett plant. Photo courtesy of Boeing.

in four topics: Smart Homes, Energy Storage Across Scales, Atoms to Airplanes: Designer/Engineered Aerospace Materials, and Protein Design for Therapeutic and Biotech Applications. In addition to the United States, participants attended from 10 EU countries: Belgium, the Czech Republic, Denmark, Finland, France, Germany, Italy, Luxembourg, Norway, and the United Kingdom.

The session on Smart Homes covered recent developments in miniature sensors, wireless sensors, and mobile computing and the associated opportunities to instrument homes with systems that can use information about human behavior to support improvements in everyday life. The speakers described emerging smart home technologies and provided their perspectives on how these technologies could transform homes from passive living spaces to interactive, supportive environments. Talks highlighted radio system requirements to ubiquitously connect smart home objects to the cloud, with a brief review of current wireless technologies; a new generation of (1) electricity and water sensing systems that can provide consumption data for each appliance or device from single sensing points and (2) low-power wireless sensors that use the electrical wiring in a building as an antenna to increase range and lower the power consumption of wireless sensors; smart environments for decision support in health care; and the link between smart home technologies and greater energy efficiency and sustainability.

The transition of energy systems from fossil to renewable sources presents many challenges, particularly the intermittency of renewable energy, which requires large reserves of energy storage. Speakers in the session on Energy Storage across Scales described the potential of new battery innovations and their role in the coming decade as well as the untapped potential and scope of chemical energy storage technologies that could transform chemical production and fuels. The first two talks addressed battery technologies. One presenter discussed batteries for grid-scale energy storage, with a focus on using the chemical compound Prussian blue to meet the challenges of both power and energy applications. The next talk concerned the role of novel materials for battery separators in improving the thermal stability of Li-ion batteries to enhance safety and energy and power density. The second half of the session concerned chemical energy storage technologies, with talks on (1) options for hydrogen production and engineering challenges for the dynamic operation of chemical processes linked to intermittent energy sources, and (2) the use of biogenic feedstocks to synthesize suitable fuels as liquid energy storage systems.

Aerospace engineers strive to find the right materials and manufacturing processes for airplanes to make them lighter, stronger, more durable, and easy to manufacture. Presentations in the Atoms to Airplanes session described key components of this endeavor: multifunctional materials development (e.g., nanoenhanced composites and intelligent materials with embedded sensors), advanced manufacturing technology, and multiscale simulation. The speakers reported on efforts to harness the unique properties of nanoscale graphene structures to develop multifunctional composite structures; the use of cellular architectures across scales to develop a new class of lightweight materials with unprecedented structural properties; progress and challenges in the modeling of composite material fractures across scales; and the possible development of highly novel designs from the emergence of integrated multiscale modeling methodology for aircraft.

In the past decade protein design has seen important methodological advances—for example, in the redesign of natural enzymes to extend their fields of application and the design of novel proteins from scratch—and these technologies have been integrated in rational engineering approaches for therapeutic purposes.

The final session of the meeting, Protein Design for Therapeutic and Biotech Applications, included three presentations on the design of novel enzymes for reactions not catalyzed by naturally occurring biocatalysts, their applications, and their impact on a sustainable future; new concepts and software tools for efficient and rational design of enzymes for biotechnological applications; and efforts to redesign biological systems—to understand spatial and temporal regulation of the fundamental processes of life—and impacts on control of kinase activity in living cells.

A poster session on the first afternoon served as both an icebreaker and an opportunity for participants to share information about their research and technical work. On the second afternoon the group was privileged to have a VIP tour of Boeing's Everett plant, the largest building in the world by volume, where Boeing's 747s, 767s, 777s, and the new 787 Dreamliner are assembled. This was followed by a stop at the Museum of Flight where attendees viewed exhibits of 150 historic air- and spacecraft and other aviation artifacts before having dinner in the museum's Red Barn, Boeing's original manufacturing plant.

The dinner speaker on the first evening was Dr. Greg Hyslop, vice president and general manager of Boeing Research and Technology. In his presentation, "Driving Innovation: The Future of Materials Development," he outlined the history of aerospace materials, advances brought about by the use of composites, concurrent technologies driven by new materials development, and what needs to be done to accelerate understanding and use of those materials. He closed by emphasizing the critical need for a skilled workforce and technology pioneers to continue innovation in aerospace materials—something needed in all fields of engineering.

Financial support for the symposium was provided by The Boeing Company, The Grainger Foundation, US National Science Foundation, NATF, and various sponsors of EU attendees' travel.

The next EU-US FOE will be held October 16–18, 2016, in Finland, with the Technology Academy Finland taking on the organizational role for the EU side. Chris Floudas will continue as US cochair of the organizing committee, and Harri Kulmala, chief executive officer of the Finnish Metals and Engineering Competence Cluster in Tampere, will serve as EU cochair.

NAE has been hosting an annual US Frontiers of Engineering meeting since 1995. For more information about the symposium series or to nominate an outstanding engineer to participate in future Frontiers meetings, contact Janet Hunziker at the NAE Program Office at jhunziker@nae.edu.

# A Message from NAE Vice President Corale Brierley

Corale Brierley

I was delighted to begin my tenure as NAE vice president last July, and am happy to report that 2014 was a successful and productive fundraising year. The year also marked the 50th Anniversary of the NAE, culminating at the Annual Meeting, and the completion of our 50th Anniversary Campaign. The NAE relies heavily on philanthropy to provide almost 30% of the funding that enables the Academy to advance the well-being of the nation by promoting a vibrant engineering profession and providing independent advice to our nation. We sincerely appreciate your involvement, generosity, and continuous support!

The spirited participation of our members—your generous ideas, time, and support—has always driven the NAE forward. Our members are vital to our success, by both making personal philanthropic investments and serving as advocates for the NAE and the engineering profession to their communities—students, parents, educators, policymakers, business leaders, and the public locally, nationally, and globally.

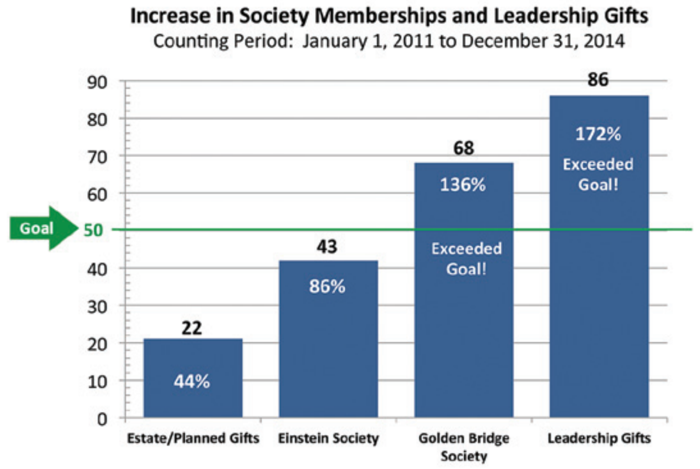
In 2014 the NAE raised over \$7.4 million in new gifts and pledges to support our efforts to strengthen the engineering profession and engage the public about the benefits and opportunities engineering presents to people and society. Annual unrestricted support reached almost \$2.5 million, including \$1.5 million to the NAE Independent Fund—the overwhelming majority of it from NAE members. The number of donors grew 9%, from 722 in 2013 to 786, while at the same time sustaining the 2014 annual member giving participation rate at a high point of 30%.

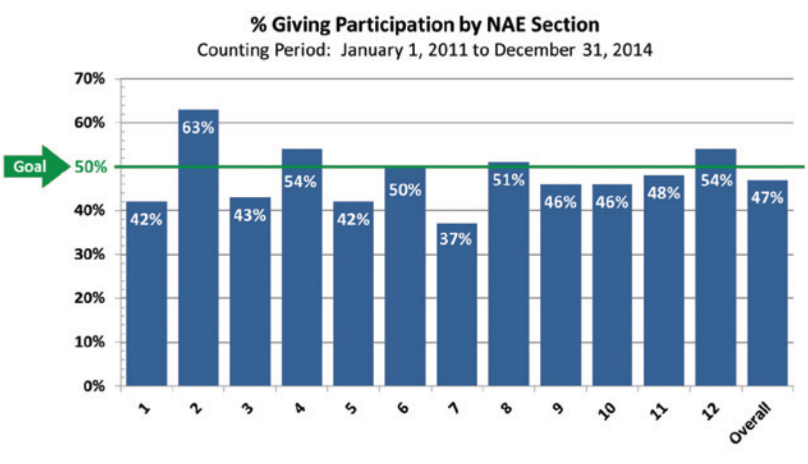
Private funds not only provide core support for the NAE each year but allow us both to initiate new projects that lack federal sponsorship and to expand the scope and impact of current programs. Without these important funds, the NAE would not have a solid foundation from which to sustain our activities and impact. Here are a few highlights of 2014.

### 50th Anniversary

In 2011, under the leadership of Chuck Vest, the NAE embarked on a four-year fundraising effort to celebrate 50 years of engineering leadership and service to the nation.

We also used the occasion of the 50th Anniversary to raise awareness among the general public, and especially among students, of engineering's immense contributions to society by launching the



Engineering for You (E4U) video contest and commissioning a series of essays. The essays and the E4U contest winners were unveiled at the 2014 Annual Meeting and 50th Celebration, and received very positive feedback. The Annual Meeting also had record attendance and particularly engaging speakers.

The occasion of our 50th Anniversary also highlighted the important role of donors in the success of the NAE. As noted above, approximately 30% of our annual budget comes from private funds, and approximately 30% of you, our members, make a gift to the NAE each year. To build momentum for our giving program, we set several ambitious fundraising goals around the theme of "50 for 50." In 2012 we exceeded the Leadership goal of securing 50 new gifts of $50,000 or more. By the end of 2013 we had exceeded the goal of 50 new Golden Bridge Society members. Sections 2, 4, 6, 8, and 12 met or surpassed the 50% giving participation goal for the sections, and others were very close and have seen remarkable improvement. Dedicated volunteers from Sections 2, 3, 5, 8, 9, and 11 stepped up to help—and spurred a strong increase in their section's participation—by personally encouraging their fellow section members to make gifts in honor of the 50th. And several corporate partners, listed on pages 81–83, helped celebrate this milestone by sponsoring some of our 50th Anniversary activities. The graphs on page 67 illustrate our progress toward achieving the goals of our Anniversary Campaign.

### Ursula Burns Challenge

In 2014 **Ursula Burns** ('13), chair and CEO of Xerox, challenged members of the classes of 2012, 2013, and 2014 to collectively give $100,000 to enable a stronger, more proactive NAE. We are excited to report that over $300,000 was raised for this challenge and the giving participation rate from the three classes was 37%. Many thanks to Ursula and the members who joined in this initiative and assisted with our 50th Anniversary goal of 50% giving participation.

### Charles M. Vest President's Opportunity Fund

As Chuck's term as president was drawing to a close and in celebration of the 50th Anniversary, we established the *Charles M. Vest Opportunity Fund* in 2012, to honor his presidency and his tireless efforts in advocating for and promoting engineering. We were deeply saddened to lose Chuck in December 2013. I hope many of you were able to join us at the NAS Building on February 20, 2014, to celebrate his life and legacy.

I'm pleased to report that $5 million in gifts, pledges, and gift intentions were received for this important fund in Chuck's memory. This past year, the fund helped support the EngineerGirl program and some of the public understanding of engineering activities for the 50th Anniversary, including the E4U video contest. It will continue to supplement existing programs, seed new initiatives, and support exploratory studies, as directed by future presidents, while at the same time honoring Chuck and his work at the NAE. This fund will empower the NAE to be more proactive in leading and identifying initiatives to benefit the nation and engineering profession. Any gift to the Vest President's Opportunity Fund counted toward the 50th Anniversary Campaign. We thank all the donors who contributed so generously to honor Chuck. (See pages 75–76 for a full list of contributors.)

Thank you to everyone who contributed to the 50th Anniversary Campaign and to our success. Through your support, the NAE is in an enhanced position to strengthen its voice on national policy; work to increase the number, quality, and diversity of engineering graduates; advance our quality of life; and enhance national capacity for innovation and global competitiveness. If you have any questions or would like to make a contribution to the NAE, please contact Radka Nebesky at 202.334.3417 or RNebesky@nae.edu.

### Outstanding Contributions and Commitments

All contributions are greatly appreciated, and all of them make a difference in the work of the NAE. The following gifts and commitments show extraordinary leadership and dedication to the Academy. Names in bold are NAE members.

- The Grainger Foundation pledged $3 million to support the Frontiers of Engineering program (FOE) and create The Grainger Foundation FOE Grants, which help foster and enable new interdisciplinary collaboration among FOE participants.
- Lockheed Martin Corporation committed $1 million to sponsor the second Global Grand Challenges Summit, to be held in China in September 2015.
- The NAE saw revocable and irrevocable gift expectancies grow by $800,000, thanks to six members who included the NAE in their estate plans and/or as a beneficiary of their retirement accounts.

- Peter O'Donnell and the O'Donnell Foundation contributed $500,000 to the Charles M. Vest President's Opportunity Fund.
- **Irwin ('76)** and Joan **Jacobs** directed over $300,000 in 2014 from their donor-advised fund at the Jewish Community Foundation of San Diego to the Charles M. Vest President's Opportunity Fund, bringing their total support of the Vest Fund to $1 million.
- The Charles Stark Draper Laboratory provided over $300,000 for expenses associated with awarding and presenting the Charles Stark Draper Prize for Engineering and in sponsorship of the 50th Anniversary.
- ExxonMobil Corporation provided $250,000 to fund the next video contest, called Engineering for You 2 (E4U2), to engage young people in learning about the opportunities engineering can provide to people and society by addressing the Grand Challenges for Engineering. The deadline to enter was March 2, 2015. Winners will be announced at the 2015 annual meeting.
- John F. McDonnell, member of the Presidents' Circle, and the JSM Charitable Trust gave $250,000 to the Frontiers of Engineering Education symposia in 2014, bringing their total support of the program to $1 million. The FOEE program brings together some of the nation's most engaged and innovative engineering educators in order to recognize, reward, and promote effective, substantive, and inspirational engineering education through a sustained dialogue among the emerging generation of innovative faculty. Since its inception five years ago, FOEE has spurred the creation of a community of engineering educators whose innovative teaching methods are helping to improve 21st century engineering education and strengthen our nation's workforce.
- The United Engineering Fund (UEF) committed nearly $150,000 for a worldwide crowdsourcing competition called "The Next MacGyver." The project is seeking ideas for a scripted television show featuring a female engineer character in a leading role. The goal of the competition is to create a historic TV series that inspires young people, especially women, to pursue careers in engineering. Teaming up with the University of Southern California's Viterbi School of Engineering (USC Viterbi), in collaboration with the MacGyver Foundation and Lee Zlotoff (creator of the popular TV series *MacGyver*), the competition was launched during the 2015 National Engineers Week and has received significant national and international press coverage (*Good Morning America*, NPR, the *Los Angeles Times*, *New York Times*, ABC news, and *Washington Post*, among many others).
- Council member **Fran Ligler ('05)** and her husband George have committed $100,000 for a matching gift challenge over five years to encourage current and future NAE Section 2 members to support the academy.
- **Raymond S. Stata ('92)** contributed close to $100,000 to the NAE Independent Fund.

### Loyal Donors

Gifts made to the NAE year after year by our members and friends demonstrate a steadfast commitment to our mission and work. As a regular long-time donor to the NAE to support the work I so strongly believe in, I am genuinely grateful to the people who have contributed for 20 years or more. Please see pages 76–77 for the complete list.

Private funds now make up almost a third of the NAE's yearly budget. Simply put, we would not be able to operate without them. Your support is essential not only in providing core support but also in expanding the scope and impact of current projects and initiating new ones.

On behalf of the NAE Council and president **Dan Mote**, I thank you for your participation in the 50th Anniversary Campaign and throughout 2014. Our generous members, friends, partner corporations, foundations, government sponsors, and other supporters make all the difference in our ability to positively impact our world and to continue advocating for engineering. I am deeply grateful for your generosity, continued involvement, and unwavering support of the NAE mission.

I look forward to getting to know more of our dedicated and generous members, donors, and staff as we work together to secure resources for the NAE's important work.

# 2014 Honor Roll of Donors

## Annual Giving Societies

The National Academy of Engineering gratefully acknowledges the following members and friends who made charitable contributions to the NAE, and those NAE members who supported the Committee on Human Rights, a joint committee of the three academies during 2014. The collective, private philanthropy of these individuals has a great impact on the NAE and its ability to be a national voice for engineering. We acknowledge contributions made as personal gifts or as gifts facilitated by the donor through a donor-advised fund, matching gift program, or family foundation.

***Ursula Burns ('13), Chair and CEO of Xerox, generously gave $100,000 to the NAE in celebration of the 50th Anniversary and to encourage philanthropy among newer NAE members. She challenged members of the classes of 2012, 2013, and 2014 to collectively give $100,000 to enable a stronger, more proactive NAE. The members who participated in the Burns Challenge are noted with the ◊ symbol.***

## Catalyst Society

*$100,000 to $500,000*

Joan and Irwin Jacobs
Mary and Howard* Kehrl
Asta* and William W. Lang
Raymond S. Stata

*Friends*

John F. McDonnell
Peter O'Donnell, Jr.

*$50,000 to $99,999*

Bharati and Murty Bhavaraju◊
James O. Ellis, Jr.◊
Elisabeth Paté-Cornell
Jonathan J. Rubinstein
David E. Shaw◊
John C. Wall
Ken Q. Xie◊

## Rosette Society

*$25,000 to $49,999*

Olivia and Peter Farrell◊
George and Ann Fisher
Kent Kresa
Asad M., Gowhartaj, and Jamal Madni
Clayton Daniel and Patricia L. Mote
Jaya and Venky Narayanamurti
Richard F. and Terri W. Rashid
Richard P. Simmons
Arnold and Constance Stancell
Gary and Diane Tooker

## Challenge Society

*$10,000 to $24,999*

Gordon Bell
Daniel and Frances Berg
Becky and Tom Bergman
Barry W. Boehm
Lewis M. Branscomb
Lenore and Rob Briskman◊
Lance and Susan Davis
Nicholas M. Donofrio
Dotty and Gordon England◊
Nan and Chuck Geschke
Martin E. and Lucinda Glicksman
Robert W. Gore
John O. Hallquist
Hugh D. Hibbitt◊
Chad and Ann Holliday
Michael W. Hunkapiller
Ray R. Irani◊
Jane and Norman N. Li
Frances and George Ligler
Robin K. and Rose M. McGuire
Narayana Murthy and Sudha Murty
John Neerhout, Jr.
Roberto Padovani
Larry* and Carol Papay
Simon Ramo
Henry M. Rowan
Henry and Susan Samueli
Maxine L. Savitz
David B. and Virginia H. Spencer◊

◊ Ursula Burns Challenge
*Deceased

Charlotte and Morris Tanenbaum
James M. and Ellen Weston Tien
James A. Trainham and Linda D. Waters
Ghebre E. Tzeghai◊
Adrian Zaccaria
Elias A. Zerhouni◊

**Charter Society**

*$1,000 to $9,999*

Linda M. Abriola
Rodney C. Adkins
Ronald J. Adrian
Alice Merner Agogino
John L. Anderson
John C. Angus
Seta and Diran Apelian
Frank F. Aplan
Kenneth E. Arnold
Wm. Howard Arnold
Thomas W. Asmus
Kamla and Bishnu S. Atal
Daniel and Monica Atkins◊
David Atlas
Nadine Aubry
Ken Austin
Wanda M. Austin
Arthur B. Baggeroer
William F. Baker
Martin Balser◊
Margaret K. Banks◊
James E. Barger
Harrison H. and Catherine C. Barrett◊
Forest Baskett III
Craig H. Benson◊
Leo L. Beranek
Howard Bernstein◊
Peter J. Bethell◊
Lorenz T. Biegler◊
Mark P. Board◊
Mark T. Bohr
Rudolph Bonaparte
Dushan Boroyevich◊
Paul F. Boulos◊
Kathleen and H. Kent Bowen
Craig T. Bowman◊
Stephen P. Boyd◊
Corale L. Brierley
James A. Brierley
Andrei Z. Broder
Andrew Brown, Jr.
John H. Bruning
George* and Virginia Bugliarello
Ursula Burns◊ and Lloyd Bean
Xianghong Cao
Federico Capasso
Stuart K. Card
François J. Castaing
Corbett Caudill
Sigrid and Vint Cerf
Selim A. Chacour
Jean-Lou A. Chameau
Chau-Chyun Chen
Josephine Cheng
Stephen Z.D. Cheng
Weng C. Chew◊
Sunlin Chou
Uma Chowdhry
Richard M. Christensen
John and Assia Cioffi
Philip R. Clark
G. Wayne Clough
James J. Coleman◊
Joseph M. Colucci
Harry M. Conger
Stuart L. Cooper
Ross and Stephanie Corotis
Gary L. Cowger
Alan W. Cramb◊
Natalie W. Crawford
Robert L. Crippen◊
Steven L. Crouch◊
Glen T. Daigger
David E. Daniel
Ruth A. David
L. Berkley Davis
Carl de Boor
Pablo G. Debenedetti
Raymond F. Decker
Thomas B. Deen
Robert H. Dennard
George E. Dieter
Daniel W. Dobberpuhl
Earl H. Dowell
Elisabeth M. Drake
Robert M. Drake, Jr.
James J. Duderstadt
Susan T. Dumais
Robert and Cornelia Eaton
Thomas F. Edgar◊
Charles Elachi
Farouk El-Baz
Iraj Ershaghi◊
James L. Everett III
Robert R. Everett
Thomas E. Everhart
James A. Fay
Robert E. Fenton
Gregory L. Fenves◊
Katherine W. Ferrara◊
Leroy M. Fingerson
Tobie and Daniel J.* Fink
Bruce A. Finlayson
Anthony E. Fiorato
Robert E. Fischell
Edith M. Flanigen
Samuel C. Florman
Robert C. and Marilyn G. Forney
Heather and Gordon Forward
Curtis W. Frank◊
William L. and Mary Kay Friend
Douglas W. Fuerstenau
Theodore V. Galambos
Huajian Gao◊
Donald P. Gaver
Arthur Gelb
Arthur and Helen Geoffrion
Penny and Bill George,◊ George Family Foundation
Louis V. Gerstner, Jr.
Paul H. Gilbert
Richard D. Gitlin
Eduardo D. Glandt
Earnest F. Gloyna
Arthur L. and Vida F. Goldstein
Mary L. Good
Joseph W. Goodman
W. David Goodyear◊
Paul E. Gray
Hermann K. Gummel
John C. Hancock
James S. Harris, Jr.
Kenneth E. Haughton
Janina and Siegfried Hecker
Robert W. Hellwarth
Larry L. Hench
Chris T. Hendrickson
John L. Hennessy
Narain G. Hingorani
David and Susan Hodges
Lester A. Hoel
Urs Hölzle◊
Edward E. Hood, Jr.
Leroy E. Hood
Edward E. Horton
John R. Howell
John R. Huff◊
J. Stuart Hunter
Mary Jane Irwin
Kenji Ishihara

◊ Ursula Burns Challenge
*Deceased

Leah H. Jamieson
George W. Jeffs
Barry C. Johnson
David W. Johnson, Jr.
Michael R. Johnson
G. Frank Joklik
Anita K. Jones
James W. Jones◊
Chanrashekhar Joshi◊
Norman P. Jouppi◊
David L. Joyce◊
Eric W. Kaler
Paul and Julie Kaminski
Melvin F. Kanninen
John and Wilma Kassakian
Jon E. Khachaturian
Diana S. and Michael D. King
James L. Kirtley
Geraldine Knatz◊
Albert S. Kobayashi
Robert M. and Pauline W. Koerner
Charles E. Kolb, Jr.◊
Demetrious Koutsoftas
Lester C.* and Joan M. Krogh
David J. Kuck
Thomas F. Kuech
Richard T. Lahey, Jr.
Louis J. Lanzerotti
Cato and Cynthia Laurencin
Enrique J. Lavernia◊
Hau L. Lee
Raphael Lee◊ and Kathy Kelley
James U. Lemke
Ronald K. Leonard
Frederick J. Leonberger
Burn-Jeng Lin
Jack E. Little
Robert G. Loewy
Gerald H. Luttrell◊
Lester L. Lyles
William J. MacKnight
Thomas and Caroline Maddock
Artur Mager
Arunava Majumdar
George C. Maling, Jr.
Henrique S. Malvar◊
Hans Mark
David A. Markle
W. Allen Marr
Robert D. Maurer
Dan Maydan
Jyotirmoy Mazumder◊
Larry V. McIntire
Kishor C. Mehta
Edward W. Merrill◊
Richard A. Meserve
Robert M. Metcalfe◊
R.K. Michel
James J. Mikulski
Richard B. Miles
Richard K. Miller
Charles A. Mistretta◊
James K. and Holly T. Mitchell
Nandita and Sanjit K. Mitra
John A. Montgomery◊
Edward and Stephanie Moses
Cherry A. Murray
Dale and Marge* Myers
Cynthia J. and Norman A. Nadel
Albert Narath
David Nash
Robert M. and Marilyn R. Nerem
Robert E. Nickell*
Paul D. Nielsen
William D. Nix
Ronald and Joan Nordgren
Matthew O'Donnell
Susan and Franklin M. Orr, Jr.
Kwadwo Osseo-Asare
Bernhard O. Palsson
Bradford W. and Virginia W. Parkinson
Claire L. Parkinson
Neil E. Paton
John H. Perepezko
Thomas K. Perkins
Pete Petit
Emil Pfender
Craig E. Philip◊
Julia M. Phillips
William P. Pierskalla
Franz F. Pischinger
Stephen M. Pollock
H. Vincent Poor
William F. Powers
Donald E. Procknow
William R. Pulleyblank
Henry H. Rachford, Jr.
Prabhakar Raghavan
Doraiswami Ramkrishna
Ekkehard Ramm
Bhakta B. Rath
Buddy D. Ratner
Raj Reddy
Kenneth and Martha Reifsnider
Gintaras V. Reklaitis
Eli Reshotko
Thomas J. Richardson
Ronald L. Rivest
Anne and Walt Robb
Richard J. and Bonnie B. Robbins
Bernard I. Robertson
C. Paul Robinson
Thomas E. Romesser
Alton D. Romig, Jr.
Howard B. Rosen
Murray W. Rosenthal
William B. Russel
Andrew P. Sage
Vinod K. Sahney
Steven B. Sample
John M. Samuels, Jr.
Linda S. Sanford
Robert E. Schafrik◊
Richard Scherrer
Jan C. Schilling◊
John H. Schmertmann
Ronald V. Schmidt
Henry G. Schwartz, Jr.
Lyle H. Schwartz
Charles L. Seitz
Martin B. and Beatrice E. Sherwin
Daniel P. Siewiorek
Krishna P. Singh◊
Alvy R. Smith
Alfred Z. Spector and Rhonda G. Kost
Robert F. and Lee S. Sproull
Jery R. Stedinger◊
Richard J. Stegemeier
Gunter Stein
Gregory Stephanopoulos
Kenneth E. Stinson
William D. Strecker
Ivan E. Sutherland
John and Janet Swanson
James M. Symons
Eva Tardos
Ratan N. Tata◊
George Tchobanoglous
Matthew V. Tirrell
John J. Tracy◊
Richard H. Truly
A. Galip Ulsoy
Raymond Viskanta
Thomas H. Vonder Haar
Robert and Robyn Wagoner
John E. Warnock
Darsh T. Wasan
Michael S. Waterman◊
Julia and Johannes Weertman
Robert J. Weimer
Andrés Weintraub Pohorille◊
Robert M. and Mavis E. White
Willis S. White, Jr.
Sheila E. Widnall

◊ Ursula Burns Challenge
*Deceased

Sharon L. Wood◊
Herbert H. Woodson
Edgar S. Woolard, Jr.
Richard N. Wright
Wm. A. Wulf
Israel J. Wygnanski
Beverly and Loring Wyllie
William W-G. Yeh
Yannis C. Yortsos
A. Thomas Young
William and Sherry Young
Zarem Foundation
Xingdong Zhang◊
Steven J. Zinkle◊
Mary Lou and Mark D. Zoback
Stacey I. Zones◊

*Friends*

Jo F. Berg
Kristine L. Bueche
Neil and Natasha Chriss
Marilyn Heebner
Evelyn S. Jones
Isabelle M. Katzer
Douglas Larson
Toby Wolf
Anonymous

**Other Individual Donors**

Hiroyuki Abe
H. Norman Abramson
Hadi Abu-Akeel
Kurt Akeley and Jenny Zhao
Montgomery M. Alger
Charles A. Amann
Cristina H. Amon
John G. Anderson
Stig A. Annestrand
George E. Apostolakis
Ali S. Argon
Robert C. Armstrong
Frances H. Arnold
R. Lyndon Arscott
James R. Asay
Jamal J. Azar
Donald W. Bahr
Rodica A. Baranescu
Grigory I. Barenblatt
Mark A. Barteau
Jordan* and Rhoda Baruch
James B. Bassingthwaighte
Ray H. Baughman
Zdenek P. Bazant
Georges and Marlene Belfort
Marsha J. Berger
Toby Berger
Philip A. Bernstein
Vitelmo V. Bertero
John R. and Pierrette G. Birge
Harvey W. Blanch
Jack L. Blumenthal
Alfred Blumstein
F. Peter Boer
William J. Boettinger
Lillian C. Borrone
Frank Bowman
Peter R. Bridenbaugh
James P. Brill
Frederick P. Brooks, Jr.
Alan C. Brown
Howard J. Bruschi
Jack E. Buffington
Ned H. Burns
Anne and John Cahn
Robert Calderbank
James D. Callen
Joe C. Campbell
Max W. Carbon◊
E. Dean Carlson
Albert Carnesale
John R. Casani
William Cavanaugh
Don B. Chaffin
A. Ray Chamberlain
Douglas M. Chapin
Vernon L. Chartier
Gang and Tracy Chen
Shu and Kuang-Chung Chien
Anil K. Chopra
Andrew R. Chraplyvy
Virginia S.T. Ciminelli◊
Paul Citron and Margaret Carlson Citron
John L. Cleasby
Seymour B. Cohn
Richard A. Conway
Esther M. Conwell*
Richard W. Couch, Jr.
Arthur Coury
Eugene E. Covert
James Q. Crowe
Lawrence B. Curtis
Ernest L. Daman
Paul D. Dapkus
Edward E. David, Jr.
Delbert E. Day
Morton M. Denn
Joseph M. DeSimone
Robert C. DeVries
Frederick H. Dill
Robert H. Dodds
John E. Dolan
Albert A. Dorman
David A. Dornfeld◊
Irwin Dorros
E. Linn Draper, Jr.
T. Dixon Dudderar
James M. Duncan
Floyd Dunn
Ira Dyer
David A. Dzombak
Peter S. Eagleson
Lewis S. Edelheit
Elazer R. Edelman◊
Daniel C. Edelstein
Helen T. Edwards
Bruce R. Ellingwood
Richard E. Emmert
Joel S. Engel
John V. Evans
Charles Fairhurst
Robert M. Fano
Essex E. Finney, Jr.
Millard and Barbara Firebaugh
John W. Fisher
Peter T. Flawn
Christodoulos A. Floudas
Maria Flytzani-Stephanopoulos◊
Robert E. Fontana
G. David Forney, Jr.
Harold K.* and Betty Forsen
Judson C. French
Eli Fromm
Shun Chong Fung
Zvi Galil
Ronald L. Geer
John H. Gibbons
Don P. Giddens
Maryellen L. Giger
Jacqueline Gish
George J. Gleghorn
Fred Glover
Richard J. Goldstein
Steve and Nancy Goldstein
John B. Goodenough
James A. Gosling
Roy W. Gould
Robert K. Grasselli
Irene Greif
Gary S. Grest
Ignacio E. Grossmann
Karl A. Gschneidner
Laura M. Haas
Donald J. Haderle

◊Ursula Burns Challenge
*Deceased

Carol K. Hall
William J. Hall
Thomas L. Hampton
John M. Hanson
Alan J. Heeger
Adam Heller
Martin Hellman
Arthur H. Heuer and Joan Hulburt
George J. Hirasaki
John P. Hirth
J. Brent and Margaret Hiskey
Allan S. Hoffman
Richard Hogg◊
Stanley H. Horowitz
Charles L. Hosler, Jr.
Salim M. Ibrahim
Izzat M. Idriss
Akira Ishimaru
Tatsuo Itoh
Andrew Jackson and Lillian Rankel
Linos J. Jacovides
Paul C. Jennings
Klavs F. Jensen
Marvin E. Jensen
James O. Jirsa
Donald L. Johnson
James R. Johnson
Keith P. Johnston
Marshall G. Jones
Angel G. Jordan
Aravind K. Joshi
Ahsan Kareem
Kristina B. Katsaros
Michael C. Kavanaugh
Edward Kavazanjian◊
Leon M. Keer
Chaitan Khosla
Timothy L. Killeen
Sung Wan Kim
Judson and Jeanne King
Paul C. Kocher
U. Fred Kocks
Bernard L. Koff
Max A. Kohler
Jindrich Kopecek
Bill and Ann Koros
Richard W. Korsmeyer◊
Roger B. Krieger◊
Derrick M. Kuzak
Stephanie L. Kwolek*
Bruce M. Lake
James L. Lammie
David A. Landgrebe
Robert S. Langer
Carl G. Langner
Robert C. Lanphier III
Ronald G. Larson
Alan Lawley
Edward D. Lazowska
Sidney Leibovich
Margaret A. LeMone
Johanna M.H. Levelt Sengers
Milton Levenson
Herbert S. Levinson
Salomon Levy
Paul A. Libby
Peter W. Likins
Yu-Kweng M. Lin
Kuo-Nan Liou
Nathan and Barbara Liskov
Andrew J. Lovinger
William R. Lucas
Verne L. Lynn
John W. Lyons
J. Ross and Margaret Macdonald
Malcolm MacKinnon III
Alfred U. MacRae
Thomas J. Malone
James W. Mar
William F. Marcuson III
Robert C. Marini
John L. Mason
David K. Matlock
William C. Maurer
William J. McCroskey
M.D. McIlroy
Ross E. McKinney
Diane M. McKnight◊
Robert M. McMeeking
Alan L. McWhorter
Harry W. Mergler
Angelo Miele
Antonios G. Mikos and Lydia Kavraki◊
James A. Miller
Warren F. Miller, Jr.
Keith K. Millheim
Arthur L. Money◊
Carl L. Monismith
Francis C. Moon
William B. Morgan
John W. Morris
Walter E. Morrow, Jr.
A. Stephen Morse
Joel Moses
Jose M.F. Moura◊
Jan and E. Phillip Muntz
Earll M. Murman
Devaraysamudram R. Nagaraj
R. Shankar Nair
Tsuneo Nakahara
Hyla S. Napadensky
Alan Needleman
Stuart O. Nelson
William New, Jr.
Joseph H. Newman
Elaine S. Oran
Julio M. Ottino
David H. Pai
Athanassios Z. Panagiotopoulos
Stavros S. Papadopulos
Louis C. Parrillo
David A. Patterson
Donald R. Paul
Harold W. Paxton
Donald W. Peaceman
P. Hunter Peckham
Nicholas A. Peppas
George M. Pharr◊
Mark R. Pinto
Karl S. Pister
Stephen and Linda Pope
Harry G. Poulos◊
William N. Poundstone
Priyaranjan Prasad
Michael Prats
Ronald F. Probstein
Charles W. Pryor, Jr.
Roberta and Edwin Przybylowicz
Robert A. Pucel
Rajagopal S. Raghavan
Vivian and Subbiah Ramalingam
Eugene M. Rasmusson
Jean-Michel M. Rendu
John R. Rice
Bruce E. Rittmann
Jerome G. Rivard
Leslie E. Robertson and Sawteen See
Lloyd M. Robeson
Stephen M. Robinson
Robert K. Roney
Kenneth M. Rosen
Gerald F. Ross
Hans T. Rossby
Yoram Rudy
Joseph C. Salamone
Gurmukh S.* and Harriet Sarkaria
Peter W. Sauer
Thorndike Saville, Jr.*
Robert F. Sawyer
George W. Scherer
Geert W. Schmid-Schoenbein
Fred B. Schneider
Jerald L. Schnoor
William R. Schowalter
Walter J. Schrenk
Albert and Susan Schultz
Mischa Schwartz
Norman R. Scott
Bal Raj Sehgal◊
Terrence J. Sejnowski
Hratch G. Semerjian
Robert J. Serafin
F. Stan Settles
Don W. Shaw

◊ Ursula Burns Challenge
*Deceased

Thomas B. Sheridan
Ben A. Shneiderman
Michael L. Shuler
Neil G. Siegel
Arnold H. Silver
Peter G. Simpkins
Kumares C. Sinha
Jack M. Sipress
R. Wayne Skaggs
Henry I. Smith
Gurindar S. Sohi
Stuart L. Soled◊
Soroosh Sorooshian
Pol D. Spanos
George S. Springer
Dale F. and Audrey Stein
Dean E. Stephan
George Stephanopoulos
Thomas G. Stephens
Kenneth H. Stokoe II
Henry E. Stone
Howard and Valerie Stone
Lawrence D. Stone
Brian Stott
Richard G. Strauch
Gerald B. Stringfellow
Stanley C. Suboleski
Rodney J. Tabaczynski
Robert L. Taylor
Lewis M. Terman
Spencer R. Titley
Neil E. Todreas
Alvin W. Trivelpiece
Stephen D. Umans
John M. Undrill
Andries van Dam
Theodore Van Duzer
Moshe Y. Vardi
Walter G. Vincenti
Harold J. Vinegar
Irv Waaland
Wallace R. Wade
Steven J. Wallach
C. Michael Walton
John D. Warner
Warren and Mary Washington
John T. Watson
Wilford F. Weeks
James Wei
Sheldon Weinbaum
Sheldon Weinig
Jasper A. Welch, Jr.
David A. Whelan
Margot and David C.* White
Robert M. White
J. Turner Whitted
David A. Woolhiser
Eli Yablonovitch
Les Youd
Laurence R. Young
Paul Zia
Ben T. Zinn
Charles F. Zukoski
Anonymous (3)

*Friends*

John Arganian
Harriet Bogdonoff
Steve S. Chen
Kwang Chin Kim
Richard Colman
James Dixon
Clara K. Ellert
Frances P. Elliott
Harold and Beverly Frost
Sharon P. Gross
Tina Hedrick
Paul Hertelendy
Theodore Irra
Arthur Kaufman
Edward Kinner
Kin Ping Lee
Deborah Levey
Kathleen Lynch Mills
Catherine McGraw
Shannon Meyer
Michele H. Miller
Radka Z. Nebesky
John Noel
Andrew Oakley
Sallie O'Neill
Ryszard Pryputniewicz
Marlin and Dorothy Ristenbatt
Georgia Scordelis
Verna W. Spinrad
Elizabeth W. Toor
Katherine Tracy
David Wilkie
Carol and David Williams
Peter, Denise, Amy, and Heather Williams

**Charles M. Vest President's Opportunity Fund**

In recognition of NAE members and friends who gave generously to the Charles M. Vest President's Opportunity Fund in 2014 to honor and remember NAE's ninth president, Chuck Vest. We acknowledge contributions made as personal gifts or as gifts facilitated by the donor through a donor-advised fund, matching gift program, or family foundation.

Linda M. Abriola
Alice Merner Agogino
Seta and Diran Apelian
Wm. Howard Arnold
Daniel and Monica Atkins
Zdenek P. Bazant
Daniel and Frances Berg
Howard Bernstein
John H. Bruning
Ursula M. Burns and Lloyd Bean
Sigrid and Vint Cerf
Jean-Lou A. Chameau
Gang and Tracy Chen
Weng C. Chew
Neil and Natasha Chriss
Edward E. David, Jr.
James J. Duderstadt
Elazer R. Edelman
Olivia and Peter Farrell
George and Ann Fisher
Harold and Beverly Frost
Arthur L. and Vida F. Goldstein
Paul E. Gray
James S. Harris, Jr.
Janina and Siegfried Hecker
Andrew Jackson and Lillian Rankel
Joan and Irwin Jacobs
Michael R. Johnson
Leon M. Keer
Sidney Leibovich
Robert M. Metcalfe
Richard K. Miller
Edward and Stephanie Moses
Cherry A. Murray
William D. Nix
Ronald and Joan Nordgren
Peter O'Donnell, Jr.
Kwadwo Osseo-Asare
Bernhard O. Palsson
Larry* and Carol Papay
David A. Patterson
Stephen M. Pollock
Ryszard Pryputniewicz
William R. Pulleyblank
Marlin and Dorothy Ristenbatt
Howard B. Rosen
Charles L. Seitz
Ben A. Shneiderman
Richard P. Simmons
George S. Springer
Arnold and Constance Stancell
Raymond S. Stata

◊ Ursula Burns Challenge
*Deceased

Richard H. Truly
John C. Wall
Sheila E. Widnall
David Wilkie
Carol and David Williams
Laurence R. Young

**Tributes**

*In memory of Jordan Baruch* – Rhoda Baruch and the Baruch Fund
*In memory of Robert R. Berg* – Jo F. Berg
*In memory of Marjana Boroyevich* – Dushan Boroyevich
*In memory of Esther M. Edelman* – Elazer R. Edelman
*In memory of John Frank Elliott* – Frances P. Elliott
*In memory of Howard S. Jones, Jr.* – Evelyn S. Jones
*In memory of Charles C. Ladd* – Craig H. Benson, Kwang Chin Kim, Richard Colman, James Dixon, Edward Kinner, Douglas Larson, Deborah Levey, Kathleen Lynch Mills, W. Allen Marr, Catherine McGraw, James K. and Holly T. Mitchell, Katherine Tracy, Peter Williams
*In memory of Shakunthala* – Devaraysamudram R. Nagaraj
*In memory of Ernest Smerdon* – Soroosh Sorooshian
*In memory of Chang-Lin Tien* – Arunava Majumdar
*In memory of Baranimir von Turkovich* – Subbiah Ramalingam

*In honor of Martin Balser* – Arthur Kaufman
*In honor of Lester C. Krogh* – Joan Krogh
*In honor of Robert Langer* – Cato and Cynthia Laurencin
*In honor of Gretchen Meyer* – Shannon Meyer
*In honor of C. D. (Dan) Mote, Jr.* – Cato and Cynthia Laurencin
*In honor of George Stegemeier* – Harold J. Vinegar

**Loyalty Society**

In recognition of members and friends who have made gifts to the National Academy of Sciences, National Academy of Engineering, or Institute of Medicine for at least 20 years. We acknowledge contributions made as personal gifts or as gifts facilitated by the donor through a donor-advised fund, matching gift program, or family foundation. Names in bold are NAE members.

Herbert L. Abrams
**H. Norman Abramson**
**Andreas** and Juana **Acrivos**
Bruce and Betty Alberts
**Clarence R. Allen**
**Charles A. Amann**
Wyatt W. Anderson
Edward M. Arnett
**Wm. Howard Arnold**
Daniel L. Azarnoff
Jack D. Barchas
Jeremiah A. Barondess
**Stephen D. Bechtel, Jr.**
John C. Beck
**Gordon Bell**
Paul Berg
Diane and Norman Bernstein
**Lewis M. Branscomb**
John and Sharon Brauman
Donald D. Brown
**Harold Brown**
Kristine L. Bueche
**George*** and Virginia **Bugliarello**
William B. Carey
Purnell W. Choppin
James McConnell Clark
John A. Clements
Michael D. Coe
Pedro M. Cuatrecasas
**Irwin Dorros**
W.G. Ernst
Harold J. Fallon
Harvey V. Fineberg and Mary E. Wilson
Tobie and **Daniel J.* Fink**
**Robert C.** and Marilyn G. **Forney**
**Harold K.*** and Betty **Forsen**
T. Kenneth Fowler
Hans and Verena Frauenfelder
Carl Frieden
**Theodore V. Galambos**
Joseph G. Gall
David V. Goeddel
Robert B. Griffiths
**Adam Heller**
Ernest M. Henley
**David** and Susan **Hodges**
Joseph F. Hoffman
William N. Hubbard, Jr.
J. David Jackson
Andre T. Jagendorf
Samuel L. Katz and Catherine M. Wilfert
**Max A. Kohler**
James S. and Elinor G.A. Langer
**Louis J. Lanzerotti**
**Gerald** and Doris **Laubach**
Judith R. Lave
**Robert G. Loewy**
**Thomas** and Caroline **Maddock**

*Deceased

Anthony P. Mahowald
Vincent T. Marchesi
**Hans Mark**
**James F. Mathis**
Christopher F. McKee
Mortimer Mishkin
Arno G. Motulsky
Elaine and **Gerald* Nadler**
Jaya and **Venky Narayanamurti**
Philip and Sima Needleman
**Robert M.** and Marilyn R. **Nerem**
Elena and Stuart Nightingale
**Ronald** and Joan **Nordgren**
Peter O'Donnell, Jr.
Gilbert S. Omenn and Martha A. Darling
George W. Parshall
Gordon H. Pettengill
Frank Press
**Simon Ramo**
Janet and Lester Reed
**Jerome G. Rivard**
R. Duncan* and Carolyn Scheer Luce
**William R. Schowalter**
Maxine F. Singer
Louis Sokoloff
**Raymond S. Stata**
Rosemary A. Stevens
Lubert and Andrea Stryer
F. William Studier
Paul and Pamela Talalay
Charlotte and **Morris Tanenbaum**
Anita and George Thompson
George H. Trilling
Roxanne and Karl K.* Turekian
Martha Vaughan
**Raymond Viskanta**
**Andrew** and Erna* **Viterbi**
Peter K. Vogt
George D. Watkins
**Julia** and **Johannes Weertman**
Herbert Weissbach
**Robert M.** and Mavis E. **White**
Catherine M. Wilfert
Gerald N. Wogan
Anonymous

### Lifetime Giving Societies

We gratefully acknowledge the following members and friends who have made generous charitable lifetime contributions. Their collective, private philanthropy enhances the impact of the Academies to advise the nation on issues of science, engineering, and medicine.

### Einstein Society

In recognition of members and friends who have made lifetime contributions of $100,000 or more to the National Academy of Sciences, the National Academy of Engineering, or the Institute of Medicine. We acknowledge contributions made as personal gifts or as gifts facilitated by the donor through a donor-advised fund, matching gift program, or family foundation. Names in bold are NAE members.

*$10 million and above*

**Arnold** and Mabel **Beckman***
**Bernard M. Gordon**
Daniel E. Koshland, Jr.*
George P. Mitchell*

*$5 million to $10 million*

Donald Bren
**William R.** and Rosemary B. **Hewlett***
Fred Kavli*
Peter O'Donnell, Jr.
Dame Jillian Sackler

*$1 million to $5 million*

Bruce and Betty Alberts
Richard and Rita Atkinson
**Norman R. Augustine**
**Craig** and Barbara **Barrett**
**Jordan*** and Rhoda **Baruch**
**Stephen D. Bechtel, Jr.**
**Harry E. Bovay, Jr.***
Harvey V. Fineberg and Mary E. Wilson
Cecil H. Green*
Joan and **Irwin Jacobs**
Kenneth A. Jonsson*
Tillie K. Lubin*
John F. McDonnell
The Ambrose Monell Foundation
**Gordon** and Betty **Moore**
**Robert*** and Mayari **Pritzker**
Richard L. and Hinda G. Rosenthal*
Jack W. and Valerie Rowe
Fritz J. and Dolores H. Russ Prize Fund of the Russ College of Engineering and Technology at Ohio University
Raymond and Beverly Sackler
Bernard* and Rhoda Sarnat
Leonard D. Schaeffer
Sara Lee and Axel Schupf
Anonymous (2)

*Deceased

*$500,000 to $1 million*

Rose-Marie and Jack R. Anderson
**John** and Elizabeth **Armstrong**
Kenneth E. Behring
**Gordon Bell**
Elkan R.* and Gail F. Blout
Carson Family Charitable Trust
Charina Endowment Fund
Ralph J. and Carol M. Cicerone
James McConnell Clark
Henry David*
Richard Evans*
Eugene Garfield Foundation
Penny and **Bill George**, George Family Foundation
William T.* and Catherine Morrison Golden
**Thomas V. Jones***
Cindy and **Jeong Kim**
**Ralph** and Claire **Landau***
Asta* and **William W. Lang**
**Ruben F.*** and Donna **Mettler**
**Dane** and Mary Louise **Miller**
Philip and Sima Needleman
Oliver E. and Gerda K. Nelson*
Gilbert S. Omenn and Martha A. Darling
Shela and **Kumar Patel**
William J. Rutter
Herbert A. and Dorothea P. Simon*
**Raymond S. Stata**
Roy and Diana Vagelos
**Alan M. Voorhees***
Anonymous (1)

*$250,000 to $500,000*

The Agouron Institute
**W.O. Baker***
Warren L. Batts
Clarence S. Coe*
Theodore Geballe
Jerome H.* and Barbara N. Grossman
William R. Jackson*
Robert L. and Anne K. James
Mary and **Howard* Kehrl**
Janet and **Richard M.* Morrow**
Ralph S. O'Connor
**Kenneth H. Olsen***
Ann and **Michael Ramage**
**Simon Ramo**
Anne and **Walt Robb**
Stephen* and Anne Ryan
**Henry** and Susan **Samueli**
H.E. Simmons*
Judy Swanson
Ted Turner
Leslie L. Vadasz
**Charles M.*** and Rebecca M. **Vest**

*$100,000 to $250,000*

**Holt Ashley***
Francisco J. and Hana Ayala
**William F. Ballhaus, Sr.***
**Thomas D.*** and Janice H. **Barrow**
H.H. and Eleanor F. Barschall*
**Elwyn** and Jennifer **Berlekamp**
Diane and Norman Bernstein
Bharati and **Murty Bhavaraju**
**Erich Bloch**
David G. Bradley
**Lewis M. Branscomb**
Sydney Brenner
**George*** and Virginia **Bugliarello**
Malin Burnham
**Ursula Burns** and Lloyd Bean
**John** and Assia **Cioffi**
**Paul Citron** and Margaret Carlson Citron
**A. James Clark**
**W. Dale** and Jeanne C. **Compton**
John D. Corbett*
**Lance** and Susan **Davis**
Roman W. DeSanctis
**Robert** and Florence **Deutsch**
Paul M. Doty*
Charles W. Duncan, Jr.
George and Maggie Eads
**Robert** and Cornelia **Eaton**
Dotty and **Gordon England**
Olivia and **Peter Farrell**
Michiko So* and Lawrence Finegold
Tobie and **Daniel J.* Fink**
**George** and Ann **Fisher**
**Harold K.*** and Betty A. **Forsen**
**William L.** and Mary Kay **Friend**
**William H.** and Melinda F. **Gates III**
Nan and **Chuck Geschke**
Jack and Linda Gill
George and Christine Gloeckler
Christa and Detlef Gloge
Estate of Avram Goldstein
**Robert W. Gore**
**Paul** and Judy **Gray**
Corbin Gwaltney
**John O. Hallquist**
Margaret A. Hamburg and Peter F. Brown
William M. Haney III
**George** and Daphne **Hatsopoulos**
**John L. Hennessy**
Jane Hirsh
**Chad** and Ann **Holliday**
M. Blakeman Ingle
Richard B. Johnston, Jr.
**Anita K. Jones**
**Trevor O. Jones**
**Thomas Kailath**
Yuet Wai and Alvera Kan
**Leon K.** and Olga **Kirchmayer***
Frederick A. Klingenstein
William I. Koch
Gail F. Koshland
Jill Howell Kramer
**Kent Kresa**

*Deceased

**John W. Landis***
Janet and Barry Lang
**Gerald** and Doris **Laubach**
**David M.*** and Natalie **Lederman**
Bonnie Berger and **Frank Thomson Leighton**
**Frances** and George **Ligler**
Whitney and Betty MacMillan
**Asad M.**, Gowhartaj, and Jamal **Madni**
Davis L. Masten and Christopher Ireland
**Roger L. McCarthy**
**Robin K.** and Rose M. **McGuire**
William W. McGuire
Burt and Deedee McMurtry
G. William* and Ariadna Miller
Stanley L. Miller*
Joe and Glenna Moore
David and Lindsay Morgenthaler
**Clayton Daniel** and Patricia L. **Mote**
Ellen and **Philip Neches**
Susan and **Franklin M. Orr, Jr.**
**David Packard***
**Charles** and Doris **Pankow***
**Larry** and Carol **Papay**
**Jack S. Parker***
Edward E. Penhoet
**Allen E.*** and Marilynn **Puckett**
**Richard F.** and Terri W. **Rashid**
**Henry M. Rowan**
**Joseph E.** and Anne P. **Rowe***
**Maxine L. Savitz**
Wendy and **Eric Schmidt**
**David E. Shaw**
**Richard P. Simmons**
**Robert F.** and Lee S. **Sproull**
Georges C. St. Laurent, Jr.
**Arnold** and Constance **Stancell**
Edward C. Stone
**John** and Janet **Swanson**
Charlotte and **Morris Tanenbaum**
**Peter** and Vivian **Teets**
**Gary** and Diane **Tooker**
Martha Vaughan
**Andrew** and Erna* **Viterbi**
**John C. Wall**
**Robert** and Joan **Wertheim**
**Robert M.** and Mavis E. **White**
John C. Whitehead
**Wm. A. Wulf**
**Ken Q. Xie**
Tachi and Leslie Yamada
**Adrian Zaccaria**
**Alejandro Zaffaroni***
Janet and Jerry Zucker
Anonymous (1)

### Golden Bridge Society

In recognition of NAE members and friends who have made lifetime contributions totaling $20,000 to $99,999. We acknowledge contributions made as personal gifts or as gifts facilitated by the donor through a donor-advised fund, matching gift program, or family foundation. Names in bold are NAE members.

*$50,000 to $99,999*

**William F. Allen, Jr.**
Jane K. and **William F. Ballhaus, Jr.**
**Barry W. Boehm**
Kristine L. Bueche
**William Cavanaugh**
**Joseph V. Charyk**
Lester and Renee Crown
**Ruth A. David**
**Nicholas M. Donofrio**
**James O. Ellis, Jr.**
**Thomas E. Everhart**
**Robert C.** and Marilyn G. **Forney**
**Michael W. Hunkapiller**
**Robert E. Kahn**
**Paul** and Julie **Kaminski**
Rita Vaughn and **Theodore C.* Kennedy**
**Johanna M.H. Levelt Sengers**
Joan M. and **Frank W.* Luerssen**
Darla and **George E. Mueller**
Cynthia J. and **Norman A. Nadel**
Jaya and **Venky Narayanamurti**
**John Neerhout, Jr.**
**Ronald** and Joan **Nordgren**
**Roberto Padovani**
**Elisabeth Paté-Cornell**
**Ronald L. Rivest**
Ellen and **George A.* Roberts**
**Jonathan J. Rubinstein**
**Warren G. Schlinger**
**Leo John*** and Joanne **Thomas**
**Julia** and **Johannes Weertman**
**Sheila E. Widnall**

*$20,000 to $49,999*

**Andreas** and Juana **Acrivos**
**Rodney C. Adkins**
**Alice Merner Agogino**
**Clarence R. Allen**
Valerie and **William A. Anders**
Seta and **Diran Apelian**
**Wm. Howard Arnold**
Kamla and **Bishnu S. Atal**
**Clyde** and Jeanette **Baker**
**William F. Banholzer**
**David K. Barton**
**Daniel** and Frances **Berg**
Becky and **Tom Bergman**
**R. Byron Bird**
Diane and **Samuel W. Bodman**
Kathleen and **H. Kent Bowen**

*Deceased

**Rodney A. Brooks**
**Harold Brown**
**Corbett Caudill**
**Selim A. Chacour**
**Josephine Cheng**
**Sunlin Chou**
**Uma Chowdhry**
**G. Wayne Clough**
**Joseph M. Colucci**
**Malcolm R. Currie**
**Ruth M. Davis*** and Benjamin Lohr
Mary P. and **Gerald P.* Dinneen**
**E. Linn Draper, Jr.**
**Mildred S. Dresselhaus**
**James J. Duderstadt**
**Stephen N. Finger**
**Edith M. Flanigen**
**Samuel C. Florman**
Bonnie and **Donald N.* Frey**
**Elsa M. Garmire** and Robert H. Russell
**Richard L.** and Lois E. **Garwin**
**Arthur** and Helen **Geoffrion**
**Louis V. Gerstner, Jr.**
**Martin E.** and Lucinda **Glicksman**
**Arthur L.** and Vida F. **Goldstein**
**Mary L. Good**
**Joseph W. Goodman**
**Paul E. Gray**
**Delon Hampton**
**Wesley L. Harris**
Janina and **Siegfried Hecker**
**Robert** and Darlene **Hermann**
**David** and Susan **Hodges**
Bettie and **Kenneth F.* Holtby**
**Edward E. Hood, Jr.**
**Edward G.*** and Naomi **Jefferson**
**Min H. Kao**
**John** and Wilma **Kassakian**
**James R.*** and Isabelle **Katzer**
**Robert M.** and Pauline W. **Koerner**
**James N. Krebs**
**Lester C.*** and Joan M. **Krogh**
**Charles C. Ladd**
**Cato** and Cynthia **Laurencin**
**Yoon-Woo Lee**
Jane and **Norman N. Li**
**Jack E. Little**
**Thomas** and Caroline **Maddock**
**Artur Mager**
**Thomas J. Malone**
**James F. Mathis**
**James C. McGroddy**
**Richard A. Meserve**
**James K.** and Holly T. **Mitchell**
**Van** and Barbara **Mow**
**Cherry A. Murray**
**Narayana Murthy** and Sudha Murty
**Dale** and Marge* **Myers**
**Robert M.** and Marilyn R. **Nerem**
**Simon Ostrach**
**Arogyaswami J. Paulraj**
**Paul S. Peercy**
**Donald E. Petersen**
**Dennis J. Picard**
**John W.** and Susan M. **Poduska**
Joy and **George* Rathmann**
**Eberhardt*** and Deedee **Rechtin**
**Kenneth** and Martha **Reifsnider**
**Jerry Sanders III**
**Linda S. Sanford**
**Roland W. Schmitt**
**Donald R. Scifres**
**Martin B.** and Beatrice E. **Sherwin**
**David B.** and Virginia H. **Spencer**
**Joel S. Spira**
**Richard J. Stegemeier**
**Henry E. Stone**
**Stanley D. Stookey**
**Daniel M. Tellep**
**David W. Thompson**
**James M.** and Ellen Weston **Tien**
**Raymond Viskanta**
**Robert** and Robyn **Wagoner**
**Daniel I. Wang**
**Albert R.C.** and Jeannie **Westwood**
**Willis S. White, Jr.**
**John J. Wise**
**Edgar S. Woolard, Jr.**
**A. Thomas Young**

### Heritage Society

In recognition of members and friends who have included the National Academy of Sciences, National Academy of Engineering, or Institute of Medicine in their estate plans or made some other type of planned gift to the Academies. Names in bold are NAE members.

**Andreas** and Juana **Acrivos**
**Gene M.** and Marian **Amdahl**
**Betsy Ancker-Johnson**
**John C. Angus**
**John** and Elizabeth **Armstrong**
**Norman R. Augustine**
Jack D. Barchas
**Harrison H.** and Catherine C. **Barrett**
Stanley Baum
Clyde J. Behney
**Daniel** and Frances **Berg**
Paul Berg
Elkan R.* and Gail F. Blout
Enriqueta C. Bond
Daniel Branton
Robert and Lillian Brent
**Corale L. Brierley**
**James A. Brierley**
Lenore and **Rob Briskman**
Kristine L. Bueche
Dorit Carmelli
Peggy and Thomas Caskey
**A. Ray Chamberlain**
Linda and Frank Chisari
Rita K. Chow
John A. Clements
D. Walter Cohen
Morrel H. Cohen
Stanley N. Cohen
Colleen Conway-Welch
**Ross** and Stephanie **Corotis**
Ellis and Bettsy Cowling
Molly Joel Coye
Barbara J. Culliton
**Malcolm R. Currie**
Peter N. Devreotes

*Deceased

**Mildred S. Dresselhaus**
**Gerard W. Elverum**
Emanuel and Peggy Epstein
Tobie and **Daniel J.*** **Fink**
**Robert C.** and Marilyn G. **Forney**
**Arthur** and Helen **Geoffrion**
**Paul H. Gilbert**
**Martin E.** and Lucinda **Glicksman**
George and Christine Gloeckler
Christa and Detlef Gloge
**Joseph W. Goodman**
Chushiro* and Yoshiko Hayashi
**Larry L. Hench**
Thomas S. Inui
Richard B. Johnston, Jr.
**Anita K. Jones**
Jerome Kagan
Diana S. and **Michael D. King**
Norma M. Lang
Asta* and **William W. Lang**
**Daniel P. Loucks**
R. Duncan* and Carolyn Scheer Luce
**Thomas** and Caroline **Maddock**
**Artur Mager**
Jane Menken
Arno G. Motulsky
**Van** and Barbara **Mow**
Guido Munch
Mary O. Mundinger
Philip and Sima Needleman
Norman F. Ness
**Ronald** and Joan **Nordgren**
Gilbert S. Omenn and Martha A. Darling
**William*** and Constance **Opie**
**Bradford W.** and Virginia W. **Parkinson**
**Zack T. Pate**
Frank Press
**Simon Ramo**
James J. Reisa, Jr.
Alexander Rich
Emanuel P. Rivers
**Richard J.** and Bonnie B. **Robbins**
C. Ruth and Eugene Roberts
**James F. Roth**
Esther and Lewis Rowland
Sheila A. Ryan
Paul R. Schimmel
Stuart F. Schlossman
Rudi* and Sonja Schmid
Kenneth I. Shine
Robert L. Sinsheimer
**Arnold** and Constance **Stancell**
H. Eugene Stanley
Rosemary A. Stevens
**John** and Janet **Swanson**
John A. Swets
**Esther S. Takeuchi**
Paul and Pamela Talalay
**John C. Wall**
**Robert** and Joan **Wertheim**
Maw-Kuen Wu
**Wm. A. Wulf**
Tilahun D. Yilma
Michael Zubkoff
Anonymous (2)

## Foundations, Corporations, and Other Organizations

### Lifetime

In recognition of foundations, corporations, and other organizations that have given gifts or grants totaling $1 million or more to the National Academy of Sciences, National Academy of Engineering, or Institute of Medicine. Names in bold have supported the NAE.

*$25 million or more*

**Carnegie Corporation of New York**
**The Ford Foundation**
The Bill & Melinda Gates Foundation
**The Robert Wood Johnson Foundation**
**W.M. Keck Foundation**
W.K. Kellogg Foundation
The Koshland Foundation

*$10 million to $25 million*

**Arnold and Mabel Beckman Foundation**
**The Charles Stark Draper Laboratory**
The William and Flora Hewlett Foundation
Howard Hughes Medical Institute
The John D. and Catherine T. MacArthur Foundation
**The Andrew W. Mellon Foundation**
The Cynthia and George Mitchell Foundation
**Alfred P. Sloan Foundation**

*$5 million to $10 million*

Michael and Susan Dell Foundation
**The Grainger Foundation**
The Irvine Company
Kaiser Permanente
The Kavli Foundation
The Pew Charitable Trusts
**The Rockefeller Foundation**

*Deceased

*$1 million to $5 million*

American Board of Family Medicine
American Cancer Society, Inc.
American Legacy Foundation
American Public Transportation Association
America's Health Insurance Plans Foundation
Amgen, Inc.
Association of American Railroads
AstraZeneca Pharmaceuticals LP
**AT&T Corporation**
Atkinson Family Foundation
The Atlantic Philanthropies (USA)
**Craig & Barbara Barrett Foundation**
**Battelle**
**S.D. Bechtel, Jr. Foundation**
Blue Shield of California Foundation
**The Boeing Company**
Bristol-Myers Squibb Company
Burroughs Wellcome Fund
The California Endowment
California HealthCare Foundation
Margaret A. Cargill Foundation
**Chevron Corporation**
**Chrysler Group LLC**
The Commonwealth Fund
**The Dow Chemical Company**
**E.I. du Pont de Nemours & Company**
**Eastman Kodak Company**
The Ellison Medical Foundation
**ExxonMobil Corporation**
**ExxonMobil Foundation**
**Ford Motor Company**
**General Electric Company**
**General Motors Company**
GlaxoSmithKline
William T. Grant Foundation
Great Lakes Protection Fund
The Greenwall Foundation
The John A. Hartford Foundation
**Hewlett-Packard Company**
**Intel Corporation**
**International Business Machines Corporation**
Johnson & Johnson
The JPB Foundation
**JSM Charitable Trust**
Ewing Marion Kauffman Foundation
The Susan G. Komen Breast Cancer Foundation
Daniel E. Koshland, Jr. Family Fund
The Kresge Foundation
Eli Lilly and Company
**Lockheed Martin Corporation**
Richard Lounsbery Foundation
Josiah Macy, Jr. Foundation
Merck & Company, Inc.
Merck Company Foundation
**Microsoft Corporation**
The Ambrose Monell Foundation
**Monsanto Company**
**Gordon and Betty Moore Foundation**
National Multiple Sclerosis Society
**Northrop Grumman Corporation**
Nuclear Threat Initiative
**O'Donnell Foundation**
**The David and Lucile Packard Foundation**
Peter G. Peterson Foundation
**Pfizer, Inc.**
**Robert Pritzker Family Foundation**
Research Corporation for Science Advancement
Rockefeller Brothers Fund
Richard & Hinda Rosenthal Foundation
Raymond & Beverly Sackler Foundation
Sanofi-Aventis
The Spencer Foundation
The Starr Foundation
Robert W. Woodruff Foundation
**Xerox Corporation**

## Annual

In recognition of foundations, corporations, or other organizations that made gifts or grants to support the National Academy of Engineering in 2014.

Ruth and Ken Arnold Family Fund at the Houston Jewish Community Foundation
Arnold Charitable Fund at Schwab Charitable Fund
Avid Solutions Industrial Process Control
Hood Family Fund of the Bank of America Charitable Gift Fund
The Baruch Fund
Bell Family Foundation
David and Sharon Kuck Family Fund of the Bessemer National Gift Fund
The Boeing Company
Card Family Foundation
Castaing Family Foundation
Cornell University Foundation
Cummins, Inc.
Carl de Boor Advised Fund of the Orcas Island Community Foundation
The Charles Stark Draper Laboratory
E.I. du Pont de Nemours and Company
Ellis Family Charitable Fund at Schwab Charitable Fund
Employees Charity Organization of Northrop Grumman
ExxonMobil Corporation
ExxonMobil Foundation
Fortinet
GE Foundation
General Aero-Science Consultants, LLC
Geosynthetic Institute
Gerstner Family Foundation

The Geschke Foundation at the Silicon Valley Community Foundation
Google, Inc.
The Grainger Foundation
Gramp Foundation
Gratis Foundation
Greater Cincinnati SMPS
Indo-US Science and Technology Forum
Innovyze
International Business Machines Corporation
Joan and Irwin Jacobs Fund of the Jewish Community Foundation
W.M. Keck Foundation
Kresa Family Foundation
Lockheed Martin Corporation
Margaret and Ross MacDonald Charitable Fund of the Triangle Community Foundation
Massachusetts Institute of Technology
Mayden Philanthropic Fund of the Jewish Federation of Silicon Valley
Medtronic Foundation
Microsoft Corporation
Gordon and Betty Moore Foundation
Dale and Marge Myers Fund at the San Diego Foundation
National Action Council for Minorities in Engineering
National Financial Services
Newmont Mining Corporation
Pfizer, Inc.
Philanthropic Ventures Foundation
PJM Interconnection
The Procter & Gamble Company
Qualcomm, Inc.
Robbins Family Fund at the Seattle Foundation
Henry M. Rowan Family Foundation
Samueli Foundation
Southwest Research Institute
Ray & Maria Stata Family Charitable Fund
Ken and Ann Stinson Fund of the Omaha Community Foundation
Morris & Charlotte Tanenbaum Family Foundation
The Engineering Center Education Trust
University of Toronto
USG Foundation
Weinig Foundation
The White Family Trust
Xerox Corporation
Xie Foundation
Zarem Foundation
Zerhouni Family Charitable Foundation

**NAE 50th Anniversary Sponsors**

In recognition of foundations, corporations, or other organizations that made gifts or grants to support the 50th Anniversary of the National Academy of Engineering in 2014.

Google™ IBM
GORDON AND BETTY MOORE FOUNDATION
FORTINET®
Cummins®
DRAPER LABORATORY

We have made every effort to list donors accurately and according to their wishes. If we have made an error, please accept our apologies and contact the Development Office at 202.334.2431 or giving@nae.edu so we can correct our records.

## Mirzayan Fellows Join Program Office

Emily Hoffman

Emily Roberts

Emily Hoffman holds a BS in biomedical engineering from Case Western Reserve University and is completing a PhD in materials science and engineering at Northwestern University. Her PhD thesis focuses on the use of electron microscopy to understand nanoscale wear and corrosion of biomedical materials. Throughout her academic career, Emily has been involved in both student government and the Society of Women Engineers, and she is particularly interested in outreach and inclusion of underrepresented minorities. Outside of the lab, she is an active Delta Gamma alumna, plays IM football, and loves listening to podcasts. Through the Mirzayan Fellowship and her work with the National Academy of Engineering, she hopes to build her skills in communicating engineering to the public and to understand the intersections of science and policy. Her NAE projects include the launch of "The Next MacGyver" competition and the Engineering Innovations Radio Series.

Emily Roberts received her PhD in biomedical engineering from Duke University in fall 2014. Her doctoral research used microfluidic technology to generate hydrophilic drug-loaded polymeric delivery vehicles for applications in the treatment of peanut allergy and brain cancer. She also completed a project encouraging graduate students and postdocs to seek out career-advancing experiences during their training as part of her participation in the Emerging Leaders Institute. She received a BS in physics from Harvey Mudd College and worked as a postbaccalaureate research fellow in biophysics at the National Institutes of Health. She has cofounded several websites dedicated to personal finance and recently started speaking on personal finance for early-career PhDs. In her free time, she enjoys playing tennis and board games and rooting for the Duke Blue Devils. As a Mirzayan Fellow, Emily is excited to learn how science policy is conducted at the various levels of government and in the private and nonprofit sectors. While at the NAE, she is working with the Center for Engineering Ethics and Society on "Infusing Ethics into the Development of Engineers."

## In Memoriam

**ALBERT L. BABB**, 88, professor emeritus of nuclear engineering and chemical engineering, University of Washington, died on October 22, 2014. Dr. Babb was elected to the NAE in 1972 for engineering contributions to the development of artificial kidney systems and medical applications of nuclear energy.

**J. ROBERT BEYSTER**, 90, founder, Foundation for Enterprise Development, died on December 22, 2014. Dr. Beyster was elected to the NAE in 1989 for outstanding scientific and engineering contributions related to nuclear energy and national defense.

**ESTHER M. CONWELL**, 92, professor, University of Rochester, died on November 16, 2014. Dr. Conwell was elected to the NAE in 1980 for contributions to the semiconductor device industry and pioneering integrated optics and organic conductors.

**RALPH L. DISNEY**, 86, professor emeritus, Texas A&M University, died on November 11, 2014. Dr. Disney was elected to the NAE in 1997 for contributions in the development of the field of queueing networks and its applications.

**ARMAND V. FEIGENBAUM**, 94, retired president and CEO, General Systems Company Inc., died on November 13, 2014. Dr. Feigenbaum was elected to the NAE in 1992 for developing concepts of "Total Quality Control," and for contributions to "Cost of Quality" and quality systems engineering and practice.

**PHILIP G. HODGE**, 94, professor emeritus of mechanics, University of Minnesota, died on November 11, 2014. Dr. Hodge was elected to the NAE in 1977 for leadership in the development of methods for the analysis and design of structures stressed beyond the yield point.

**PHILIP W. LETT JR.**, 92, retired president, PWL Inc., died on June 6, 2014. Dr. Lett was elected to the NAE in 1984 for 25 years of technical and managerial contributions to the development of US combat and tactical vehicle systems.

**FREDERICK F. LING**, 87, Earnest F. Gloyna Regents Chair Emeritus in Engineering, University of Texas, died on November 8, 2014. Dr. Ling was elected to the NAE in 1977 for contributions to the understanding of friction and wear, metal cutting and forming, and the dysfunction in human joints.

**JAMES W. MAYER**, 83, Galvin Professor of Science and Engineering, Arizona State University, died on June 14, 2013. Dr. Mayer was elected to the NAE in 1984 for original contributions to ion implantation, Rutherford backscattering spectrometry, and other major aspects of solid-state engineering research and education.

**MARK V. MORKOVIN**, 97, professor of aerospace and mechanical engineering emeritus, Illinois Institute of Technology, died on October 18, 2014. Dr. Morkovin was elected to the NAE in 1987 for contributions to the understanding of instability, transition, and turbulence through outstanding research and distinguished written reviews of the field.

**GERALD NADLER**, 90, IBM Chair Emeritus in Engineering Management, University of Southern California, died on July 28, 2014. Dr. Nadler was elected to the NAE in 1986 for technical and educational leadership in industrial engineering, interdisciplinary systems planning, and design methodologies, and for technological literacy programs for nonengineers.

**FREDRIC RAICHLEN**, 82, professor of civil engineering and mechanical engineering emeritus, California Institute of Technology, died on December 13, 2014. Dr. Raichlen was elected to the NAE in 1993 for contributions to coastal engineering research and practice related to tsunamis, harbor oscillations, and wave defense of submarine pipelines.

**ANDREW P. SAGE**, 81, University Professor and First American Bank Professor, George Mason University, died October 31, 2014. Dr. Sage was elected to the NAE in 2004 for contributions to the theory and practice of systems engineering and systems management.

**THORNDIKE SAVILLE JR.**, 89, retired technical director, Coastal Engineering Research Center, US Army Corps of Engineers, died on November 5, 2014. Mr. Saville was elected to the NAE in 1977 for leadership, vision, and innovation in the field of coastal engineering.

**HARVEY W. SCHADLER**, 83, retired technical director, GE Corporate Research and Development, died on November 30, 2014. Dr. Schadler was elected to the NAE in 1991 for exceptional leadership in development and applying advanced materials and processes for the electrical and aircraft engine industries.

**S. DONALD STOOKEY**, 99, retired director of fundamental chemical research, Corning Incorporated, died on November 4, 2014. Dr. Stookey was elected to the NAE in 1977 for invention of glass, ceramics, and photo-sensitive glasses.

**CHARLES F. TIFFANY**, 84, retired executive vice president, Military Airplanes, the Boeing Company, died on October 12, 2014. Mr. Tiffany was elected to the NAE in 1984 for sustained contributions to the government and industry to provide safe, longer-life structures for aerospace systems.

**LELAND J. WALKER**, 91, founder, Northern Engineering and Testing Inc., died on December 31, 2014. Mr. Walker was elected to the NAE in 1984 for his outstanding practice as a civil engineer and for his distinguished service to the profession and engineering education.

## Calendar of Meetings and Events

| | |
|---|---|
| April 1 | Deadline for Nominations for 2015–2016 NAE Awards |
| April 9–11 | Third Annual Integrated Network on Social Sustainability (INSS) Conference<br>Charlotte; London; Lansing; Phoenix; Bend, Oregon |
| April 10 | Gordon Prize Award Ceremony<br>Northeastern University<br>Boston |
| April 16–17 | Understanding the Engineering Education-Workforce Continuum Committee Meeting |
| April 16–18 | German-American Frontiers of Engineering<br>Potsdam |
| April 20–21 | NAE Convocation with the Professional Engineering Societies |
| April 22 | NAE Regional Meeting<br>Columbia University<br>New York |
| April 27 | LinkEngineering Committee Meeting 5 |
| June 1–3 | China-America Frontiers of Engineering<br>Beckman Center<br>Irvine |
| June 23–24 | NAE Regional Meeting<br>Case Western Reserve University<br>Cleveland |

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

**Frontiers of Engineering: Reports on Leading-Edge Engineering from the 2014 Symposium.** This volume presents papers on the topics covered at the National Academy of Engineering's 2014 US Frontiers of Engineering Symposium. Every year the symposium brings together 100 outstanding young leaders in engineering to share their cutting-edge research and innovations in selected areas. The 2014 symposium was held September 11–13 at the National Academies Beckman Center in Irvine, California. The four session topics were co-robotics, battery materials, technologies for the heart, and shale gas and oil. This book, a compendium of the presenters' papers, is meant to convey the excitement of this unique meeting and to highlight innovative developments in engineering research and technical work.

NAE member **Kristi S. Anseth**, Investigator, Howard Hughes Medical Institute, Department of Chemical and Biological Engineering, University of Colorado Boulder, chaired the symposium steering committee. Paper, $44.00.

**Development Planning: A Strategic Approach to Future Air Force Capabilities.** The development and application of technology have been an essential part of US airpower, leading to a century of air supremacy. But that developmental path has rarely been straight, and it has never been smooth. This report provides recommendations to improve development planning for near-term acquisition projects, concepts not quite ready for acquisition, corporate strategic plans, and training of acquisition personnel. Developmental planning can provide the Air Force leadership with a tool to determine, over the next 20 years, what capability gaps must be filled and support development of the workforce skills needed to think strategically to close the capability gap.

NAE members on the study committee were **Paul G. Kaminski** (cochair), chair and CEO, Technovation Inc.; **W. Peter Cherry**, independent consultant, Ann Arbor, Michigan; **Robert J. Hermann**, private consultant, Bloomfield, Connecticut; Lester L. Lyles, independent consultant, Vienna, Virginia; and **Thomas E. Romesser**, retired vice president and chief technology officer, Northrop Grumman Aerospace Systems. Paper, $49.00.

**Future Directions for NSF Advanced Computing Infrastructure to Support US Science and Engineering in 2017–2020: Interim Report.** Demand for advanced computing has been growing for all types and capabilities of systems, from large numbers of single commodity nodes to jobs requiring thousands of cores; for systems with fast interconnects and for increasingly diverse applications that include data analytics as well as modeling and simulation. New models of computing, including cloud computing and publicly available/privately held data repositories, open up new possibilities for NSF and the researchers who use its supercomputing centers. To better understand the changing requirements of the science and engineering community and the importance of new advanced computing infrastructure, NSF asked that the National Research Council examine anticipated priorities and tradeoffs for advanced computing in support of NSF-sponsored science and engineering research. This report is an initial review of issues to be considered in the development of future NSF strategy, budgets, and programs for advanced computing.

NAE member **William D. Gropp**, Thomas M. Siebel Chair in Computer Science, University of Illinois at Urbana-Champaign, cochaired the study committee. Paper, $29.00.

**Reducing Coastal Risk on the East and Gulf Coasts.** Hurricane- and coastal storm–related losses have risen substantially during the past century, largely due to increases in population and development in the most susceptible coastal areas. This report evaluates the effectiveness of coastal risk reduction strategies and levels of protection along the country's East and Gulf Coasts to reduce the impacts of coastal flooding associated with storm surges. The report calls for a national approach to coastal risk management, with regional solutions and recognition of the economic, social, environmental, and life safety benefits that come from risk reduction efforts. The report recommendations will help engineers, planners, and policymakers at national, regional, state, and local levels move the nation from a primarily reactive stance to coastal disasters to an approach that invests wisely in coastal risk reduction and builds resilience among coastal communities.

NAE members on the study committee were **Gregory B. Baecher**, Glenn L. Martin Institute Professor of Engineering, Department of Civil and Environmental Engineering, University of Maryland; **Ross B. Corotis**, Denver Business Challenge Professor, Department of Civil, Environmental, and Architectural Engineering, University of Colorado Boulder; and **Robert A. Dalrymple**, Willard and Lillian Hackerman Professor of Civil Engineering, Whiting School of Engineering, Johns Hopkins University. Paper, $55.00.

**US Air Force Strategic Deterrence Analytic Capabilities: An Assessment of Tools, Methods, and Approaches for the 21st Century Security Environment.** The US strategic nuclear posture comprises nuclear-certified long-range bombers, intercontinental ballistic missiles, and submarine-launched ballistic missiles. Despite domestic consensus on the need to maintain an effective deterrent, there is no consensus on what that requires, especially in a changing geopolitical environment and with continued reductions in nuclear arms. This report identifies the analytic issues and factors that must be considered in seeking both nuclear deterrence of adversaries and assurance of allies in the 21st century. It assesses tools, methods, and approaches for improving understanding of nuclear deterrence and assurance and the extent to which failures in deterrence or assurance might be averted or mitigated by the proper choice of nuclear systems, technological capabilities, postures, and concepts of operation of US nuclear forces.

NAE members on the study committee were **John F. Ahearne**, executive director emeritus, Sigma Xi, The Scientific Research Society; **Gerald G. Brown**, Distinguished Professor of Operations Research, US Naval Postgraduate School; **Albert Carnesale**, chancellor emeritus and professor, University of California, Los Angeles; **W. Peter Cherry**, independent consultant, Ann Arbor, Michigan; and **John A. Montgomery**, director of research, US Naval Research Laboratory. Paper, $40.00.

**The Postdoctoral Experience Revisited.** The percentage of PhDs who pursue postdoctoral training is growing and spreading from the biomedical and physical sciences to engineering and the social sciences, and the average length of time spent in postdoctoral positions seems to be increasing. This report looks at current postdoctoral fellows—how many there are, where they are working, in what fields, and for how many years—and makes recommendations to improve their period of service, title and role, career development, compensation and benefits, and mentoring. Current data on demographics, career aspirations, and career outcomes for postdocs are limited, so the report calls for better data collection and sharing. A larger goal of the study is to consider ways to satisfy some of the research and career development needs of postdoctoral researchers, who are the future of the research enterprise. The recommendations of this report will help clarify the role of postdoctoral researchers and improve their status and experience.

NAE member **James D. Plummer**, professor of electrical engineering, Stanford University, was a member of the study committee. Paper, $49.95.

**Force Multiplying Technologies for Logistics Support to Military Operations.** Logistics provides the backbone for Army combat operations: without fuel, ammunition, rations, and other supplies, the Army would grind to a halt. Aircraft can move large amounts of supplies, but the vast majority must be carried on ocean-going vessels and unloaded at ports that may be at a great distance from the battlefield, increasing costs not only in economic terms but also in terms of lives lost in the movement of the materiel. This report describes new technologies and systems to meet demand at the point of need, make maintenance more efficient, improve inter- and intratheater mobility, and improve near-real-time, in-transit visibility. It provides a logistics-centric research and development investment strategy and illustrative examples of improved logistics in the future.

NAE members on the study committee were **Gerald E. Galloway Jr.** (chair), Glenn L. Martin Institute Professor of Engineering, University of Maryland, College Park; **Gerald G. Brown**, Distinguished Professor of Operations Research, US Naval Postgraduate School; **Charles R. Cushing**, president, C.R. Cushing & Co. Inc.; **Charles F. Gay**, founder, Greenstar Foundation; **Thom J. Hodgson**, Distinguished University Professor, Fitts Industrial & Systems Engineering Department, North Carolina State University; **Kaushik Rajashekara**, Distinguished Professor of Engineering and Endowed Chair, Erik Jonsson School of Engineering and Computer Science, University of Texas at Dallas. Paper, $56.00.

**India–United States Cooperation on Science and Technology for Countering Terrorism: Summary of a Workshop.** India and the United States are the world's two largest democracies, with distinguished scientific traditions and experts in a wide range of scientific-technical fields. Given these strengths and the ability to learn from one another, the US National Academy of Sciences and India's National Institute for Advanced Studies, in Bangalore, held a joint workshop to identify and examine potential areas for substantive scientific and technical cooperation that can support counterterrorism efforts through the Homeland Security Dialogue and through direct cooperation. This summary of that workshop examines biological threats; protection of nuclear facilities; security (physical and cyber) for chemicals, chemical facilities, and other critical infrastructure; and monitoring, surveillance, and emergency response. The report also identifies and examines promising areas for further Indian-US cooperation.

NAE member **Norman R. Augustine**, retired chair and CEO, Lockheed Martin Corporation, chaired the study committee. Paper, $52.00.

**Best Practices for Risk-Informed Decision Making Regarding Contaminated Sites: Summary of a Workshop Series.** The Department of Energy's Office of Environmental Management's (EM) mission is the safe cleanup of sites associated with government-led development of nuclear weapons and nuclear energy. The largest and most complex of these legacy sites have not been fully remediated, although their cleanup is proceeding under legally enforceable agreements with timelines for hundreds of milestones. EM is reviewing alternatives to increase the effectiveness and cost efficiencies of its cleanup activities, especially for sites that will have residual contamination when active cleanup is complete. This report summarizes two workshops, in October 2013 and January 2014, on best practices for risk-informed remedy selection, closure, and postclosure control of radioactive and chemically contaminated sites that present significant difficulty for remediation to unrestricted release. The report examines holistic approaches for (1) remediating sites with multiple contaminant sources and postclosure uses and (2) incorporating a sustainability framework into decision making regarding site remediation, closure, and postclosure control. It also discusses postclosure controls, assessment of long-term performance of site remedies, and best practices for risk-based remediation decisions.

NAE member **Michael C. Kavanaugh**, principal, Geosyntec Consultants, was a member of the study committee. Paper, $50.00.

The
BRIDGE

(USPS 551-240)

National Academy of Engineering
2101 Constitution Avenue NW
Washington, DC 20418

Periodicals
Postage
Paid