Summer 2021

NOISE CONTROL ENGINEERING

The BRIDGE

LINKING ENGINEERING AND SOCIETY

NATIONAL ACADEMY OF ENGINEERING

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Mission Statement of *The Bridge*

The Bridge publishes articles on engineering research, education, and practice; science and technology policy; and the interface between engineering and technology and society. The intent is to stimulate debate and dialogue both among members of the National Academy of Engineering (NAE) and in the broader community of policymakers, educators, business leaders, and other interested individuals. *The Bridge* relies on its editor in chief, NAE members, and staff to identify potential issue topics and guest editors. Invited guest editors, who have expertise in a given issue's theme, are asked to select authors and topics, and independent experts are enlisted to assess articles for publication. The quarterly has a distribution of about 7000, including NAE members, members of Congress, libraries, universities, and interested individuals all over the country and the world. Issues are freely accessible at *www.nae.edu/TheBridge*.

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The BRIDGE

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LINKING ENGINEERING AND SOCIETY

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President's Perspective

John L. Anderson and Lance A. Davis

John Anderson

Lance Davis

John Anderson (NAE) is president of the National Academy of Engineering. Lance Davis (NAE) is senior advisor to the NAE and former executive officer (1999–2015).

Where Engineers Work

The responsibility of engineering is to serve society and improve the quality of life. In support of these goals, the National Academy of Engineering celebrates and promotes the engineering profession in all its diversity, from the variety of engineering disciplines and applications to the men, women, and ethnic and racial minorities in engineering occupations and the variety of settings where they work—academia, government, nonprofits, and industry.

The NAE explicitly considers these factors on a yearly basis as it strives to elect new members who represent the totality of the profession. It is these members, highly accomplished in their fields of engineering, whose expertise ensures the credibility of academy and National Research Council reports, which are commonly referred to as the "gold standard" for government advisory reports.

The formation of the NAE was driven by a desire of prominent engineers to recognize the contributions of engineering in an academy parallel to the National Academy of Sciences, with a particular intent of recognizing the technical expertise of "practicing" engineers. The makeup of the first 25 engineers inducted in the NAE at its inception in 1964 was 52 percent from industry, 36 percent from academia, and 12 percent from "other" (government laboratories and military), indicating the strong industry bent of the academy at its formation.[1] This set an approximate benchmark for NAE work sector demographics, but over several decades the composition of the NAE's elected classes shifted significantly toward the academic sector, causing a loss of connectivity with industry.

When talking about electing the top engineers in the country, we should understand where engineers are employed. With that in mind, and with a sense of both equity and mission, in 2015 the NAE Council set the US membership requirement for business/industry at 50 percent beginning with the 2016 election cycle. The elected classes of 2016–21 have met this requirement. While the percentage is somewhat arbitrary, a quota is necessary to reflect the demographics of the profession *and* to recognize the magnitude of engineering innovations that emanate from industry.

In terms of sector demographics, many more engineers are employed in industry (76 percent) than in academia (7 percent).[2] About 85 percent of NAE members have a doctoral degree, which may be suggestive of the strong academic presence in the NAE, but the fraction of engineering doctorate holders in industry

[1] Of the 35 members elected to the National Academy of Sciences that year, 34 were employed by universities and 1 by a medical nonprofit.

[2] National Science Foundation Science and Engineering Indicators, S&E Workers in the Economy, figure 3-10: Broad S&E occupational categories, by employment sector: 2017 (https://ncses.nsf.gov/pubs/nsb20198/s-e-workers-in-the-economy)

(56 percent) is double that in 4-year academic institutions (28 percent).[3]

Of course, NAE members are chosen on the basis of accomplishments, not educational attainment, and engineers in industry drive amazing technological advances irrespective of degree. This is evident in the recipients of one of the world's preeminent awards for engineering achievement, the NAE's biennial Charles Stark Draper Prize for Engineering, which honors engineers whose accomplishments have significantly impacted society. Of the 56 Draper Prize winners, 66 percent have been in industry compared to about 16 percent in academia and 18 percent in government.

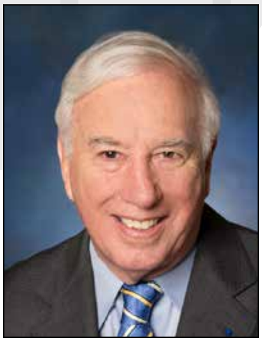
Some members have asked whether the requirement of 50 percent of members from industry runs counter to our parallel goal of diversifying the NAE with respect to gender and race/ethnicity. The data over the past 4 years indicate that this requirement is not an obstacle to the election of women and minorities: 51 percent of the members elected in 2018–21 are from industry; of these, 26 percent are women and 9 percent are underrepresented minorities. These values are largely comparable to the election of women (33 percent) and minorities (12 percent) from the academic and other sectors over the same time period.

If most engineers are employed in industry, their numbers should similarly include women and minorities. It is a matter of recognizing them. The NAE membership goals actively encourage such recognition.

The late NAE president Chuck Vest used to remark that, based on his personal contacts with members of Congress and their staff, they were very impressed that the NAE had a large fraction of members from industry. For them, it provided assurance that they were getting input from a broad base of the technical community, not only an academic view. To serve the nation, this is a perspective the NAE needs to maintain. It is important for the NAE to have the input of the business sector and for businesses to perceive the NAE as important and relevant to them.

[3] NSF Science and Engineering Indicators, S&E Workers in the Economy, table S3-6: Employment sector of S&E highest degree holders, by level and field of highest degree: 2017 (https://ncses.nsf.gov/pubs/nsb20198/data#table-block)

Introduction



C.D. Mote Jr. is Regents Professor, University of Maryland, and former NAE president (2013–19).

The NAE and Noise Control Engineering

It is my honor and great personal pleasure to introduce readers of *The Bridge* to this issue devoted to noise control engineering. In 2007 the subject was first covered in *The Bridge* during the early stages of an NAE consensus study that led to the report *Technology for a Quieter America* (*TQA*), published in 2010. You will find this issue a key follow-up to that work. I commend guest editors **George C. Maling Jr.** and Eric W. Wood for their dedicated efforts both over the years and in putting together this issue.

Background

About a half-century ago, I became interested in the control of aerodynamic noise and vibration of high-speed circular saw blades to improve the quality of the product surface and suppress the "screaming" sound created by aerodynamic vortices shed from the rotating teeth. At a meeting of the Acoustical Society of America in Hawaii in 1978, I met Adnan Akay and we initiated a friendship that is ongoing to this day. He and I went on to found the Noise Control and Acoustics Division of the American Society of Mechanical Engineers in 1981, which ASME warmly welcomed.

George Maling and **William W. Lang**, both IBM retirees and active NAE members, contributed faithfully and with unrelenting determination to noise control engineering for more than 6 decades. They founded and served as officers of the Institute of Noise Control Engineering of the USA (INCE-USA) and both were recipients of the William W. Lang Award for the Distinguished Noise Control Engineer. Bill was tirelessly dedicated to furthering worldwide recognition of noise and noise control as a distinct and critical engineering field. His passing in 2016 was a great loss to the community, but he lived his life to the fullest.

George chaired the committee that authored the *TQA* report. In 2011 he and Bill created a follow-up program to engage experts to assess specific noise issues covered in the *TQA* report and develop recommendations to improve the noise environment in the United States. The NAE first endorsed this initiative and topics on an informal basis and subsequently adopted it in 2016 through a new NAE policy allowing the opportunity for member-initiated programs. George, Bill, and other experts worked closely with the NAE in the organization, planning, and management of workshops on the particular topics of the *TQA* report.

In This Issue

In the first article George Maling and Eric Wood summarize noise control efforts and workshops over the past 15 years, with emphasis on relevant observations and recommendations from the associated reports (all of which are freely accessible online).

Adnan Akay then provides an overview of noise control engineering and the challenging education needed to prepare students for a career in this wide-ranging field. Unlike other areas of engineering, there is no specified curriculum or program in noise control engineering; Adnan identifies a range of courses to attain a fundamental and practical understanding of the field.

Noise is a factor in virtually every form of transportation, as Gregg Fleming addresses in the tracking and addressing of noise from trains, highway vehicles, and aircraft. The understanding and mitigation of transportation-related noise is partially in hand but awaits further research and fieldwork for many particular needs and opportunities.

In addition to engineering methods used to suppress noise, noise standards are a critical tool for both evaluation and management of noise. Robert Hellweg details national and international standards developed to accurately measure and report noise over decades. This information provides manufacturers and consumers a common standard as they seek to evaluate and purchase quiet products for the home and workplace.

To address noise concerns, identifying noise source is always important. Yangfan Liu, Stuart Bolton, and Patricia Davies explain acoustic source localization techniques, challenges associated with current methods, and potential applications.

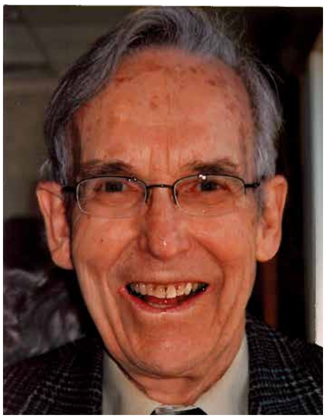
George Maling rounds out the issue's thematic articles with a compendium of resources for noise control engineering, from Buy Quiet programs and databases to professional and governmental organizations.[1]

The following experts contributed to the quality of this issue by evaluating its articles: Jim Barnes, Bennett Brooks, Gary Dylewski, Alex Gilbert, Judi Greenwald, David Herrin, Cecilia Ho, Yong-Joe Kim, Stephen Lind, Dana Lodico, William Murphy, Allan Pierce, and Don Scata.

Concluding Thoughts

Bill Lang and I had frequent discussions about the future of the NAE in all areas of interest. He was passionate in his dedication and thoughts both about the value of enhancing greater cooperation among the three National Academies and about greater engagement of the NAE members in the technical work of the National Academies. Notable progress exists there, but excellent opportunities remain. Those goals are important to the NAE. At the 2020 NAE annual meeting, President John Anderson called on more members to participate in the work of the National Research Council.

I will forever thank Bill Lang for the heart and soul that he devoted to noise and to the engagement of the NAE in noise over his 38 years of academy membership. Bill was a true treasure for noise control, for the National Academy of Engineering, and for his legions of friends and colleagues who worked with him, for him, and under him. Memory of him is perpetual.

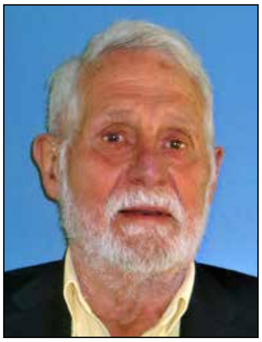


William W. Lang
(1926–2016)

[1] Note from the managing editor: We regret that we were not able to enlist an author for the column on engineering and social responsibility aspects of noise engineering.

The NAE and INCE Foundation have engaged the noise control engineering community to advance efforts to improve noise in the United States.

A Decade and a Half of Progress Toward Reducing Noise in the United States



Eric Wood

George Maling

Eric W. Wood and George C. Maling Jr.

The year 2020 marks 15 years since kick-off of the Technology for a Quieter America (TQA) project (figure 1), a joint effort of the National Academy of Engineering (NAE) and the INCE Foundation[1] to look at noise in the United States, including its sources, how it is characterized, and efforts to reduce it. The TQA project grew from one visionary noise control engineer's idea for a consensus study, and led to the landmark *Technology for a Quieter America* report (NAE 2010) as well as follow-up workshops on specific related subject areas.

Background

It was the late William (Bill) W. Lang (NAE; 1926–2016)—physicist, distinguished noise control expert, and cofounder of INCE-USA and the INCE Foundation—who in 2005 conceived and proposed a joint project with the NAE to study noise in this country. NAE president Wm. A. Wulf approved the project, with the understanding that Bill would identify funding. While the vision was initially limited to a consensus study, a series of

[1] The foundation was established in 1993 by the Institute of Noise Control Engineering of the USA (INCE-USA).

Eric Wood is cofounder and principal of Acentech Incorporated. George Maling (NAE) is managing director emeritus of INCE-USA.

FIGURE 1 Logo of the Technology for a Quieter America project of the National Academy of Engineering and INCE Foundation.

follow-on workshops have continued to gather expert perspectives in various related areas.

In preparation for the consensus study, a scoping workshop was held in Washington in October 2005. Then a series of workshops (2007–09) reviewed the state of technology in noise control engineering and considered how existing and future technologies could help reduce noise exposure in the United States.

After publication of the 2010 *TQA* report, in 2011 the National Park Service (NPS) asked the NAE "to assist the NPS in refining portions of its national noise program," accounting for the importance of quiet for both visitors and wildlife in the hundreds of NPS properties. The NAE convened park personnel and noise control specialists who, in themed workshop breakout groups, identified 17 cost-effective actions to assist park managers in controlling and reducing noise associated with transportation, maintenance, and construction in US national parks (NAE 2013).

TQA Follow-on Workshops

Since 2012 a series of follow-on workshops have convened experts to expand on selected topics covered in the *TQA* report, toward improving the noise climate in the United States. The workshops were led and financially supported by Bill Lang through the INCE Foundation, and (unless otherwise indicated in the following accounts) hosted by the NAE in its Washington facilities.[2] NAE support was provided by the Michiko So Finegold Memorial Trust. Reports of the workshops are freely accessible as PDFs on the INCE-USA website.[3]

Noisy Motorcycles: An Environmental Quality-of-Life Issue

In 1980 the EPA implemented a federal regulation to limit noise from motorcycles. But although motorcycles today come from the manufacturer with well-designed and effective exhaust systems, noise problems occur when a consumer replaces the original exhaust system with noncompliant components. Some bikers believe loudness confers safety, others just want loud bikes.

In the first follow-on workshop, held in October 2012 and sponsored by the INCE Foundation and Noise Control Foundation, 29 experts representing motorcycle manufacturers, rider organizations, government agencies, universities, noise control consultants, and the public explored ways to address problems associated with noisy motorcycles. These included federal motorcycle noise regulations that do not reflect current motorcycle design technology or operator use patterns and that preclude effective enforcement of motorcycle noise by state and local authorities.

The workshop report includes 30 recommendations for addressing these and other types of issues (INCE-USA 2013). For example, in an effort to assist state and local governments that want to reduce motorcycle noise, the report recommends that "States concerned with motorcycle noise should look to state and local governments, such as Golden, Colorado, and New Hampshire, to develop education-based programs to encourage riders to keep noise low. Find a way for states to share information on their motorcycle noise programs" (p. 54).

Cost-Benefit Analysis: Noise Barriers and Quieter Pavements

It is well recognized that highway noise is a quality-of-life issue. More than $5 billion has been spent constructing more than 3000 linear miles of roadside noise barriers in the United States.

The main source of noise emissions from highways is the interaction between vehicle tires and the road surface. Considerable research and development has

[2] Until 2016 the workshops were organized on an ad hoc basis with approval from the NAE Program Office; after that, member-initiated events were covered under NAE policy.

[3] www.inceusa.org/publications/technology-for-a-quieter-america. These summaries compliment articles published in *Noise Control Engineering Journal* and *Noise/News International*, and presented at INTER-NOISE and NOISE-CON conferences.

shown that changing the design of the road surface can reduce noise emissions.

A workshop in January 2014 addressed the costs and benefits of highway noise barriers, lower-noise road surfaces, and combinations of the two. Ten findings and recommendations are provided in the workshop report, based on presentations by 23 experts. One recommendation was "Encourage [the Federal Highway Administration] to develop guidance on the use of quieter pavements and barriers for noise abatement" (INCE-USA 2014, p. 2).

The workshop was sponsored by the INCE Foundation, the Noise Control Foundation, and the Transportation Research Board Committee on Transportation-Related Noise and Vibration, and organized in cooperation with the US Department of Transportation Volpe Center.

Reducing Employee Noise Exposure in Manufacturing: Best Practices, Innovative Techniques, and the Workplace of the Future

At this February 2014 workshop more than 20 experts discussed conservation programs in manufacturing industries, best practices and innovative techniques for engineering noise control in this context, and a vision for the manufacturing workplace of the future.

Presentations and discussions considered (i) the availability of effective low-cost techniques for the reduction of noise in industry and the design of low-noise machines for industrial use, (ii) techniques for reducing noise through changes in processes in industrial plants, and (iii) the future manufacturing environment and implications for new noise goals in manufacturing facilities (INCE-USA 2016a).

The workshop was sponsored and organized by the INCE Foundation, Noise Control Foundation, and National Institute for Occupational Safety and Health.

Engineering a Quieter America: Progress on Consumer and Industrial Product Noise Reduction

Contributions of noise control engineers have improved quality of life and the US economy by providing domestic manufacturers with the expertise to develop, produce, and sell quieter products that are desired or required nationally and globally.

This workshop, in October 2015, reviewed progress in addressing noise associated with both consumer products (from automobiles to waste disposal systems to leaf blowers) and industrial products (from air-moving devices to valves), in both categories ranging in size from small handheld devices to million-pound off-road trucks. Anticipated future noise control engineering technologies were also discussed.

Speakers represented manufacturers, consultants, trade and standards associations, universities, and a well-known consumer publication. Many of the 31 attendees had 30 to 40 years of direct engineering experience in consumer at-home products or industrial products. The event was organized by the INCE Foundation and Noise Control Foundation.

Noise control engineers improve quality of life and the US economy by providing the expertise to develop, produce, and sell quieter products.

Among the observations conveyed in the workshop report, "Product manufacturers have determined that 'quiet' pays as does 'sound quality.' Lower sound levels and enhanced sound quality both help to differentiate their products. They provide additional brand recognition. They also increase sales and help the bottom line. And it has been found that in the course of designing a product to decrease noise, sometimes performance is also bolstered" (INCE-USA 2016b, p. 145).

Engineering Technology Transfer: Research and Development for Engineering a Quieter America

Looking at current research by government, universities, and the private sector, this workshop considered which research holds promise for translation into useful, innovative noise control solutions and, ultimately, for enhancing the ability of engineers to solve problems and improve US industry competitiveness. The workshop, held in October 2016, was attended by 32 experts and organized by the INCE and Noise Control Foundations.

The report's summary of panel discussions noted, for instance, the observation of the panel on advanced methods for noise control engineering that "It is likely that development of advanced methods in noise control engineering will be computer-based (involving, for example, computational fluid dynamics, source localization, path noise control, and instrumentation). The panel's focus is on future developments in computer-supported techniques" (INCE-USA 2017a, p. 104).

Commercial Aviation: A New Era

The United States is a world leader in aviation technology. A principal focus of this workshop included step-changes in the technology of future aircraft necessary for the country to maintain both its global leadership position and the very positive trade balance that aviation brings to the US economy.

While significant progress has been made in reducing noise from commercial aircraft, additional government support in aeronautics is needed.

This workshop in May 2017 was organized by the INCE Foundation and conducted in cooperation with NASA and the FAA. It was attended by more than 60 experts representing airplane and engine manufacturers, aircraft research organizations, airlines and cargo operators, airports, universities, NASA, the FAA, consultants, and interested communities.

The vital importance of government funding required to continue X-system development in flight testing was emphasized by presenters. They also made the case that, while significant progress has been made in reducing noise from commercial aircraft, additional government support in aeronautics is needed to maintain US global leadership. This is particularly true given the immense government support provided in other countries—notably, in the European Union and China. A panel discussion on a low-noise future considered many alternatives. "Options must be kept on the table…[whether] related to the open rotor or other technology—toward achieving sought-after changes in acoustics, emissions, and energy" (INCE-USA 2017b, p. 119).

UAS and UAV (Drone) Noise Emissions and Noise Control Engineering Technology

This December 2018 workshop, organized by the INCE Foundation in cooperation with NASA and the FAA, focused on unmanned aerial systems/vehicles (UAS/UAVs), or drones. UAVs are expected to become a common part of US national airspace within the next few decades. At the workshop, experts from government, academia, and the private sector addressed future uses, noise emissions, and noise control technologies.

At the conclusion of the workshop, one participant remarked "What's next? Where do we go from here?" (INCE-USA 2020a, p. 165). Coordination among primary actors such as NATO, NASA, the FAA, and industry would be useful. And to collaborate in terms of filling data gaps, NASA might serve as a repository for UAV/UAS data for researchers as they develop models.

Noise Control Engineering Education: Session at NOISE-CON 2019

A session at the NOISE-CON 2019 conference held in August in San Diego was a follow-on to the recommendations in the 2010 *TQA* report chapter 9, "Education Supply and Industry Demand for Noise Control Specialists" (NAE 2010, p. 129):

Recommendation 9-1: Academic institutions should offer an undergraduate course in noise control engineering, broaden the scope of the engineering curriculum, and increase the pool of engineering graduates equipped to design for low noise emissions. The course could be offered as an elective in a bachelor's degree program or as part of a minor (e.g., in acoustics or interdisciplinary studies).

Recommendation 9-2: Graduate-level noise control courses should provide a balance between theory and engineering practice, without sacrificing academic rigor. The committee strongly encourages the establishment of graduate internships in industry and government agencies and thesis research programs to motivate students and build a cadre of future noise control engineers.

Recommendation 9-3: Federal agencies, private companies, and foundations with a stake in noise control should provide financial support for graduate students assisting with noise control engineering research or teaching. This support is crucial for the development of noise control professionals and noise control educators.

This session featured nine presentations by academics, consultants, and industry representatives about sources for noise control engineering education, including undergraduate and graduate courses as well as short courses available to practicing engineers.

A key question during the session was "Does demand for graduates in noise control engineering exceed supply?" The consensus: It does. Academic institutions receive many requests for noise control engineering graduates. And during the session, a participant followed up on a point made by presenters that graduate students land employment easily in noise control engineering: How can that demand be driven home to university administrators and funding sources to address the supply side of this equation?

Noise Control Engineering Education

This December 2019 workshop, attended by 28 experts, explored ways to broaden opportunities for noise control engineering education, covering the perspectives of universities, industry, government, and professional societies. Presentations addressed graduate and undergraduate educational offerings, including traditional and distance learning; continuing education courses, including short courses; educational opportunities sponsored by government agencies; and informal learning opportunities such as mentorships and involvement in professional society activities.

Noise control engineering integrates elements of electrical engineering, architectural acoustics, psychoacoustics, physiological acoustics, and a number of other subjects. Unlike traditional engineering fields, it does not have its own dedicated department at American universities. Instead, the curriculum is included in other departments, usually mechanical or aerospace engineering. Workshop presenters also considered coverage of noise control in universities' architectural programs, psychological acoustics, and the role of engineering in K–12 education.

As was discussed at the NOISE-CON session, this workshop drove home the importance of noise control engineering education in light of the very high demand for graduates in the field, which according to the consensus of the presenters far exceeds the supply.

Recommendations were developed at the end of the workshop, related to three general themes (INCE-USA 2020b, p. 113):

- Encourage an enhanced presence of noise control and related topics in existing curricula, including undergraduate and community college programs.
- Develop and promote noise control and acoustics resources, both basic and more in-depth.
- Attract interest to noise control by promoting the field, with efforts to do so through a modern lens.

Aerial Mobility: Noise Issues and Technology

This virtual workshop, held in December 2020, was organized by the INCE Foundation in cooperation with NASA and FAA as a follow-on to both the 2018 workshop on UAS/UAV noise (INCE-USA 2020a) and a recent report, *Advancing Aerial Mobility: A National Blueprint* (NASEM 2020).

> *Unlike traditional engineering fields, noise control engineering does not have its own dedicated department at US universities.*

Aerial mobility (the preferred term in the aviation community) includes urban air mobility (UAM), cargo vehicles, and drones. Noise from these vehicles is a focus area for both the FAA and NASA. The 2020 NASEM report (p. 5) stated that "Public acceptance of advanced aerial mobility, particularly noise aspects and its psychological factors, is perhaps one of the biggest challenges along with safety. Failure to address these issues could hinder advanced aerial mobility implementation."

Improved understanding of these sources and effects on communities is needed to assist government, industry, and academia in formulating plans to advance noise control technology for aerial vehicles. The following topics were discussed at the workshop:

- a report on the 2020 Quiet Drone symposium in Paris
- NATO-sponsored progress on rotor and propeller noise
- technology for the design of aerial mobility vehicles (AMVs)
- operational strategies to reduce the noise emitted by AMVs

- uses of AMVs in the private sector, with emphasis on the importance of noise
- measurement methods and metrics for determination of noise from AMVs
- noise standards and harmonization with national and international bodies
- community response to noise from AMVs
- coordination of federal requirements and state and local regulations.

Publication of the report of this virtual workshop is expected later in 2021.

Conclusion

The 10 workshops summarized above and the corresponding reports are a strong beginning to the ongoing series on important topics in noise control engineering. The *TQA* report itself was a broad-brush treatment of noise control in the United States, so there are other topics to be covered. For example, a workshop scheduled for October 19–20, 2021, will look at new technologies for noise control, and plans are being made for an event in 2022.

Acknowledgments

The cooperation of the FAA, NASA, and NIOSH in the organization of several workshops contributed greatly to the resulting reports. Tamar Nordenberg (Vie Communications) was the rapporteur and key writer of most of the INCE-USA workshop reports. The members of the steering committee for almost all the workshops were Adnan Akay (Bilkent University), Gregg Fleming (US DOT/Volpe Center), Robert Hellweg (Hellweg Acoustics), and both of us. None of this work would have been possible without William W. Lang's vision and generous funding.

References

INCE-USA [Institute of Noise Control Engineering of the USA]. 2013. Noisy Motorcycles—An Environmental Quality-of-Life Issue. Reston VA.

INCE-USA. 2014. Cost-Benefit Analysis: Noise Barriers and Quieter Pavements. Reston VA.

INCE-USA. 2016a. Reducing Employee Noise Exposure in Manufacturing: Best Practices, Innovative Techniques, and the Workplace of the Future. Reston VA.

INCE-USA. 2016b. Engineering a Quieter America: Progress on Consumer and Industrial Product Noise Reduction. Reston VA.

INCE-USA. 2017a. Engineering Technology Transfer: Research and Development for Engineering a Quieter America. Reston VA.

INCE-USA. 2017b. Engineering a Quieter America: Commercial Aviation: A New Era. Reston VA.

INCE-USA. 2020a. Engineering a Quieter America: UAS and UAV (Drone) Noise Emissions and Noise Control Engineering Technology. Reston VA.

INCE-USA. 2020b. Engineering a Quieter America: Noise Control Engineering Education. Reston VA.

NAE [National Academy of Engineering]. 2010. Technology for a Quieter America. Washington: National Academies Press.

NAE. 2013. Protecting National Park Soundscapes: Summary of a Workshop. Washington: National Academies Press.

NASEM [National Academies of Sciences, Engineering, and Medicine]. 2020. Advancing Aerial Mobility: A National Blueprint. Washington: National Academies Press.

Noise control engineering epitomizes the engineering profession since it clearly and directly pertains to technology and the public.

Noise Control Engineering and Education

Adnan Akay is a professor of mechanical engineering and provost of Bilkent University in Ankara.

Adnan Akay

Noise is often an unavoidable and ubiquitous byproduct of many systems and processes, and the more complex the system, the more difficult it is to accurately determine a priori its noise radiation characteristics. It is therefore considered more economical and effective to "design in" noise prevention measures in development than to try to "design out" using noise control techniques. In practice, however, most noise control engineering efforts address remediation and mitigation retroactively.

There is a tendency to oversimplify causes of noise and thus neglect it or equate it with vibration. Engineering curricula should clearly delineate noise and vibration and require consideration of noise in design projects whenever appropriate. A holistic systems approach in design courses can benefit from the inclusion of noise as a parameter. Educating design engineers and engineering organizations to consider noise issues as a design requirement would help in the management of noise problems, as is done in aircraft, submarine, and modern architectural design.

Noise Management: Aims and Stakeholders

Noise management generally implies reduction to acceptable levels as determined by standards, communities, legislation, and commercial competition. It also includes "shaping" noise by changing its characteristics, such as its spectrum, to make it less objectionable while retaining the signal (or information) it is meant to transmit, such as changes in an operating device or the approach of a vehicle. Noise management also concerns physical effects on structures, as in the case of sonic booms, and biological effects, as on marine life. Noise management efforts generally aim for quieter homes, workplaces, schools, hospitals, urban areas, and national parks, as well as quieter products and transportation for both communities and passengers.[1]

The pervasiveness of noise means it involves a variety of stakeholders with interests spanning quality of life, health, and economics—from technology developers and researchers to educators, users and consumers of products, businesses and industries, consultants, professional societies, governments, and the public. Federal, state, and local governments and agencies balance these stakeholder needs through policies, researchers develop new technologies to ease the apparent dichotomy between quality of life and cost, and educators contribute to the entire spectrum.

Management of the sound emitted from a source requires an understanding of its design and operational characteristics.

Noise control engineering more or less covers the range of stakeholders' interests and needs, and varies with institution type and size, from small businesses to large industries, regulatory agencies, and large and small consulting firms. Noise control engineering positions vary from a resident engineer who occasionally works on noise problems to full-fledged noise and vibration groups that include research and development.[2] The skills and knowledge needed by a noise control engineer include compliance, measurement, source identification, and suppression and inhibition of sound generation and transmission. In addition, the ability to communicate orally and in writing is important as noise control engineering directly bridges technology and society.

Understanding Noise Control Engineering

Noise control engineering follows the basic elements of noise control along the customary source-path-receiver model. Conventional wisdom advocates focusing on the noise source as the most effective approach, but this is not always possible or practical. Prevention or modification of the sound path (e.g., with barriers, walls, enclosures, or treatment with special materials) helps manage noise levels before reaching the receiver, individuals, or communities. When such methods become ineffective, receiver protection methods are employed.

Identifying Noise Sources

For noise reduction or management, a noise source can be considered a combination of *force* or *energy* sources and *acoustic* or *radiation* sources. Often, but not always, excitation that leads to sound radiation (emission) originates at a different part of the source system from where the energy reaches an efficient radiator of sound. Noise radiation from ship hulls due to diesel engines is such an example. Also, flow through a thin-walled metal duct excites the walls, which become the sound source.

Sometimes the force and sound sources are the same, as in the case of a car antenna that produces a whistling sound due to vortex shedding. Power generated by the pistons in a swash plate hydraulic pump propagates to other parts of, say, construction equipment with a crowded structure, and radiates sound from panels that it reaches. More common in multifamily dwellings is the noise of footsteps that radiates through the floor and the ceiling below.

Many complex noise sources have multiple force and acoustic sources within the system, making causal source identification more difficult. Noise control engineers use special techniques and instrumentation with signal processing capabilities to identify the sources. Management of the sound emitted from a source requires an understanding of its design and operational characteristics. These and other examples strongly suggest the importance of knowledge of diverse engineering disciplines in managing noise sources, as discussed later.

Emission, Transmission, Immission

Sound power, together with directivity, defines the inherent emission characteristics of noise sources and

[1] These subjects have been addressed in the report *Technology for a Quieter America* (NAE 2010) and in a related series of workshops (e.g., INCE-USA 2020).

[2] For a survey of noise control engineering resources, see Maling (2021) in this issue.

is usually reported as the A-weighted sound power level of a noise source. A-weighting approximates the perception of sounds by the listener with a single number (for a detailed discussion, see NAE 2010). Noise radiation then involves transmission, reflection, refraction, diffraction, absorption, and scattering as sound propagates through the environment and interacts with boundaries.

Transmission refers to force or energy paths, sound paths, and *flanking* paths (in which sound waves excite structure-borne sound waves to reach an otherwise isolated surface and radiate sound). Reducing the levels of direct sound fields before they reach a receiver, operator, home, or office generally involves barriers, walls, or enclosures. For outdoor barriers (e.g., along highways) and walls, material properties, cost, and durability play an important role.

Immission (what an individual hears) represents a source sound modified during transmission and/or by the environment in which the source and receiver are located. In an enclosed environment management of sound field requires knowledge of room or architectural acoustics, to be able to quantify the sound field by considering the reflection and absorption of sound and transmission through walls, windows, and vents. Free-hanging absorption materials in a factory help reduce noise, while balconies, ornate reliefs, and other configurations of assorted dimensions help distribute sound in a concert hall to achieve a more uniform and desirable acoustic energy density for the entire audience.

Methods for protecting the receiver from excessive noise (e.g., on airport tarmacs or near very noisy machinery in enclosed areas) include personal hearing-protection devices, such as earmuffs and noise cancelling headphones. Receiver protection also requires limiting exposure times, in keeping with established norms and legal restrictions. Knowledge of relevant ordinances, regulations, and standards is an appropriate part of noise control engineering education.

Useful, Annoying, and Luxury Noise

Although noise is described as unwanted sound, it can have useful applications. For instance, artificial or natural white noise helps mask annoying sounds, such as high-frequency squeals, and provides some privacy for conversations in offices and hospitals. Noise can also convey signals about the operation or health of a system or machine for diagnostic or detection purposes.

Conversely, submarines and helicopters need to reduce the noise they emit to avoid detection and identification. For supersonic aircraft to travel over land, efforts are underway to modify the sonic boom signature to reduce its detrimental effects on people and structures. Noise from drones, however, must balance between complete suppression to reduce disturbance and an adequate level to alert people in the vicinity to their presence for privacy.

Knowledge of psychoacoustics can help a noise control engineer assess the annoyance potential of noise.

Noise has a broad realm of impact that ranges from one extreme that can be considered "violent" (e.g., explosions) to the other extreme that can be called "luxury" noise (e.g., hush-quiet car interiors). With the abatement of dominant sources of noise in luxury cars as a result of advanced aerodynamic design and reduced engine, transmission, and road noise, previously unnoticed sounds have been "unmasked," including those of the small electric motors that raise and lower the windows and antenna and power the small pump in the fuel tank.

It is worth noting that individuals respond to the same sound immission differently depending on who is operating the proverbial leaf blower, even if it is louder than one's hairdryer. As distinct from deleterious health effects of very loud noise, annoyance resulting from noise can be summed up by quoting Milton (1644) out of context: its "annoyance and trouble of mind infuse it self [sic] into all the faculties and acts of the body...." Knowledge of psychoacoustics can help a noise control engineer assess the annoyance potential of noise. Psychoacoustics studies that date back to S.S. Stevens in the 1940s have regained renewed significance as engineering advances make it possible to modify the spectral content and amplitude of noise signatures to reduce annoyance or prevent speech interference.

Noise Control Engineering Education

The above discussion indicates that noise and thus noise control engineering represent more than a monolithic, narrow discipline. Awareness of, if not expertise in, a

BOX 1 Sample courses and areas of study for noise control education

BASIC – UNDERGRADUATE	
Dynamics	Basic acoustics
Vibrations – discrete	Noise and vibration control
Fluid dynamics	Measurement and instrumentation
ADVANCED – GRADUATE	
Advanced dynamics	Random vibrations
Advanced vibrations – continuous	Nonlinear vibrations
Advanced fluid dynamics – waves	Advanced controls
ADVANCED – SPECIALIZED	
Structural acoustics	Signal processing
Interaction of sounds and structures	Nonlinear control systems
Ocean/underwater acoustics	Wave propagation
Aeroacoustics	Ultrasonics
ADVANCED – SPECIALTY	
Psychoacoustics	Environmental noise
Audiology	Automotive noise
Audio technologies	Gear noise
Acoustics of music and speech	Thermoacoustics
Music technologies	Medical acoustics
Building acoustics	
NEEDED	
Design for low/shaped noise	

variety of subfields is a desirable attribute of an educated noise control engineer. Noise control engineering education should reflect the field's needs and practice, with a broad range and depth of applications relevant to many stakeholder groups.

Education should prepare noise control engineers to address myriad kinds of noise problems—in the home, workplace, urban areas, and national parks—and to design quieter products and vehicles. Since the effects of noise range from annoyance to harmful health impacts, noise control engineers must learn about policies and regulations intended to mitigate these adverse effects.

Preparation for Practice

Noise control engineers work in industry, government agencies, and consulting firms, and with technology developers, users and consumers, the public, and educators. The diverse interests converge through technology, policies, and economics to enhance quality of life and health. This convergence has an important role in noise control engineering education.

Noise control engineers' practice may be viewed as addressing three categories of problems: (i) well-defined, routine problems; (ii) complex system-level problems that have multiple parameters requiring optimization among them; and (iii) elusive problems without an immediately obvious solution. Problems in the second and especially third categories often require interdisciplinary backgrounds, advanced studies, and/or years of experience.

Academic preparation of a noise control engineer to deal with problems of different levels of sophistication and in different fields of application may include one or two courses as an undergraduate, a capstone project, an MS degree, and/or a PhD degree. Most such courses and programs are in mechanical engineering departments, but many interdisciplinary programs cover vibrations and acoustics as well as noise control.

Beyond academia numerous opportunities exist for nonspecialist degree holders such as short courses and online education. Occasionally nonengineers and non–degree holders also get involved in noise control engineering. In summary, multiple paths exist for noise control engineering education.

Curriculum

Noise control engineering education does not have a standard curriculum but relies on courses in selected aspects of noise control engineering. In addition to those listed in box 1, these may include aerodynamics, structural dynamics, physics, electronics, psychology, physiology, architecture, and statistics (Moss 2008).

Undergraduates who take at least two courses (and associated laboratories) in vibrations, acoustics, and noise control possess a strong foundation. A capstone project can help coalesce the knowledge gained in coursework and bring out practical aspects of noise control engineering problems.

In the absence of a noise control engineering curriculum, a master's degree in acoustics or noise control, with thesis, provides more depth and breadth than undergraduate courses and projects. Additional courses may cover topics such as continuous system vibrations, random vibrations, advanced-level acoustics, signal processing, psychoacoustics, and courses related to noise sources such as fluid dynamics and structural dynamics (Moss 2008). A graduate with a master's degree should be ready to build on this education by gaining experience working on noise control projects. The type of employment determines the additional breadth and depth of the experience gained.

A doctorate on a topic related to noise control is often awarded by a mechanical engineering, aerospace engineering, or physics department with a thesis that treats a noise control problem. Additional advanced-level courses and courses from other disciplines augment the research experience gained during development of a thesis. A doctorate better equips an engineer to address elusive and complex noise control engineering problems. The narrow and deep nature of a thesis may initially appear to confine expertise to a specific area, but the capabilities gained during the thesis work generally translate to most other applications and problems.

As with engineering education generally, experience gained from working on noise control problems is an irreplaceable education. Short courses offered by consulting firms may transmit years of experience and provide many "rules of thumb." With or without a degree, a good understanding of engineering principles can also pave the path to becoming an effective noise control engineer.

Challenges and Opportunities

Clearly, knowledge exists for educating and preparing noise control engineers. However, courses on noise control engineering are not part of the required undergraduate curriculum; they are elective and thus need to attract enough students to sustain them. Students may be drawn to courses in areas that appear attractive in the context of the job market. At the graduate level, students are generally supported by a research program, which may suggest employment potential following graduation.

Much academic research in noise control engineering has roots in large-scale funding from federal government agencies (e.g., underwater acoustics, aircraft noise). But in recent years support for noise research has decreased in favor of competing areas of study in new fields such as machine learning, nanotechnologies, bioinformatics, and genome studies. Many of these areas, as well as developments in metamaterials and sensors, for example, can enrich noise control engineering and education.

The challenge is to attract students to noise control engineering with sponsored projects that support faculty and student interests and research. Research can yield new ideas, insights, technologies, and approaches and thus excite and engage students, professors, sponsors, and even the public. And it leads to discoveries that can, for example, help mitigate emission and immission problems.

Responsibility falls on the noise control engineering community to draw on and incorporate new developments in areas to both advance the field and make it more attractive to students and employers. Integration of new technologies and discoveries—such as noise shaping with psychoacoustics, active control of vibrations and sound fields, AI for noise control at the design stage and for diagnostics, new measurement techniques with embedded nanomechanical sensors, and use of simulations and auralization[3]—all promise to enrich and bring new excitement to this field.

Experience gained from working on noise control problems is an irreplaceable education.

Emerging technologies such as electric cars and electric aircraft create new noise-related concerns and needs. What is the appropriate level and type of noise needed to ensure safety? Electric cars are adding a warning system for pedestrians. Trucks and other large vehicles are transitioning from timed beeping to a loud white noise when backing. In some airports, electric caddy carts alert pedestrians with a warning signal that may be objectionably loud. Noise control engineers have a role in developing appropriate emission and measurement technologies for these uses.

[3] Auralization is a procedure for modeling and simulating the experience of acoustic phenomena in a virtual space.

Anecdotal reports indicate that certain industries and government agencies need more noise control engineers, and may even provide in-house training in aspects of noise control.

Concluding Remarks

People everywhere are exposed to noise, whether at home, at work, or during travel or leisure activities, resulting in different degrees of irritation or risk. Laws and ordinances exist to protect the public from hazardous effects of noise. Noise control engineers have the expertise to develop and implement methods to meet regulatory requirements.

A public that is informed about noise mitigation technologies and methods would be more likely to demand solutions and ask for quieter products and processes. Professional societies should pursue partnerships with federal, state, and local governments to educate the public.

Funding agencies generally respond to ideas proposed by researchers to make a difference in a given field. Workshops that bring together researchers from industry, universities, and federal laboratories can identify research needs in a particular field to encourage funding agencies to support and give new life to education and research in that field. And special sessions at conferences can present new ideas for the development of new technologies for noise control.

Industry sponsorship of senior capstone or graduate projects is an opportunity not only to educate noise control engineers but for companies themselves to learn about the dimensions and impacts of noise.

Noise control engineering epitomizes the engineering profession since it clearly and directly pertains to technology and the public. The effective preparation of noise control engineers is an important responsibility for all stakeholders to ensure health and quality of life free of annoying and harmful noises.

References

INCE-USA [Institute of Noise Control Engineering of the USA]. 2020. Engineering a Quieter America: Noise Control Engineering Education. Reston VA.

Maling GC Jr. 2021. Resources for noise control engineering. The Bridge 51(2):41–47.

Milton J. 1644. The Doctrine and Discipline of Divorce, booke 1, chapter X. Available online at www.dartmouth.edu/~milton.

Moss J. 2008. Noise control engineering education in the USA. Noise News International 16(3):90–112.

NAE [National Academy of Engineering]. 2010. Technology for a Quieter America. Washington: National Academies Press.

Continued research and technical advances are needed to address both persistent and novel concerns in transportation-related noise.

Trains, Planes, and Automobiles: Transportation Noise in the United States

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Soundscape is the term for the acoustic environment perceived by humans in context. The human-made portion of the outdoor soundscape is largely dominated by transportation. Until transportation vehicles are truly or nearly silent, or a transformative technology emerges that either effectively isolates the noise (e.g., the Hyperloop) or obviates the need for large numbers of vehicles to move people and goods from one place to another, transportation-related noise will remain a major challenge—and a quality of life issue.

Introduction

Acousticians think of noise in terms of a source-path-receiver challenge, and it is helpful to think about individual modal contributions to the transportation noise landscape in this context.

Most professionals agree that the most effective solution to reducing noise is to reduce it at the source, but for a variety of reasons this approach is not equally viable for rail, aviation, and highway noise sources. For one thing, the three transportation modes are not all subject to federal noise standards and regulation.

The Federal Railroad Administration (FRA) is responsible for ensuring compliance with noise emission limits for railway equipment. However, these limits are set by the Environmental Protection Agency (EPA; under 40 CFR 201).

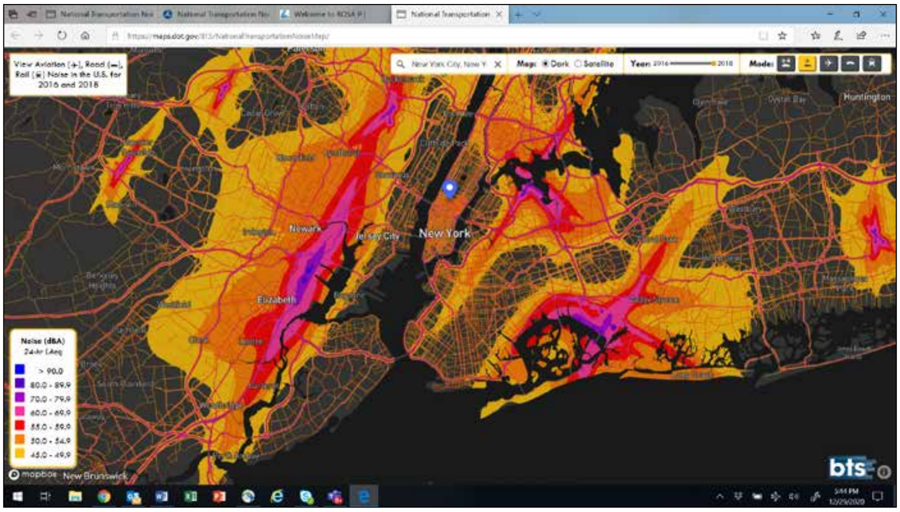

FIGURE 1 Transportation-related noise map for New York metropolitan area, 2018. Source: Bureau of Transportation Statistics.

The Federal Aviation Administration (FAA) is legally responsible for certificating aircraft noise levels (under 14 CFR part 36 and 49 USC 44715). In coordination with the National Aeronautics and Space Administration (NASA), the FAA funds research programs on reduction of noise at the source.

There is no comparable legal authority in the Department of Transportation (USDOT) for regulating noise from highway vehicles. Therefore the Federal Highway Administration (FHWA) and state DOTs have strived to reduce highway noise through the construction of noise barriers—a path-based solution to reducing noise.

This article reviews research and accomplishments in reducing rail, highway, and aircraft noise in the United States, as well as the roles of various US government agencies. It also considers current research and potential impacts of new technology such as drones, advanced air mobility, high-speed rail, and automated vehicles.

Tracking Trends in US Transportation Noise

It's useful to understand the current state of the noise problem before identifying potential solutions, whether they involve source-based fundamental noise research (e.g., aircraft-engine noise reduction), path-based approaches (e.g., highway noise barrier construction), or receiver-centric approaches (e.g., sound insulation in buildings).

In 2016 USDOT's Bureau of Transportation Statistics (BTS), with support from the department's Volpe National Transportation Systems Center, launched the National Transportation Noise Map initiative to track trends in noise related to multiple transportation modes.[1] The initiative is not intended to support regulatory or rulemaking activity, but rather to provide a repository for tracking and understanding trends in transportation-related noise over time, including consideration of population exposure.

The noise maps use simplified noise modeling assumptions to compute the 24-hour equivalent A-weighted sound level (this metric was chosen to distinguish it from USDOT regulatory metrics). Since the initiative was developed in a geospatial environment, it can be adapted for use in a variety of research topics, such as understanding both possible uses of transportation noise to mask noise from other sources and noise-related equity issues. As an example, figure 1 presents the 2018 transportation-related noise map for the New York metropolitan area.

Rail Noise

"Everybody loves the sound of a train in the distance," as Paul Simon wrote. Research supports the fact that rail noise is the least annoying of transportation noises (Janssen and Vos 2011). But that's not to say that the rail sector is without its noise challenges.

Train Horns

Train horns are the most prominent rail noise challenge. The most effective strategy to address it is to eliminate crossings through grade separation. Second is elimination of horn soundings through the use of quiet zones, where alternate safety measures are implemented (FRA 2013).

One FRA-approved alternate safety measure that has been documented to reduce community noise impact is the wayside horn installed at crossings (Hummer and Jafari 2007; Lucke and Raub 2004; Lucke et al. 2012; Multer and Rapoza 1998). While effective in limiting noise exposure to the population in the vicinity of a

[1] The map is available at https://data.bts.gov/stories/s/National-Transportation-Noise-Map/ri89-bhxh.

crossing, wayside horns have not been widely implemented. In 2010 there were 27 crossings with wayside horn installations; 10 years later the number was 55.[2]

The somewhat limited use of wayside horns is due to hurdles similar to those that plague the establishment of quiet zones: the cost of equipment and crossing upgrades, particularly if power is not available at the crossing; and the process of obtaining required approvals. In addition, wayside horns do not eliminate train horn noise entirely and may confer less benefit in terms of noise exposure compared with other quiet zone safety measures. In fact, wayside horns sometimes even increase noise exposure for the population adjacent to the crossing. Their utility must be evaluated on a site-by-site basis.

Only about 3 percent of the nation's 125,600 public at-grade roadway railroad grade crossings are in quiet zones. The GAO (2017) evaluated FRA's quiet zone rule and recommended that FRA revise its methods for analyzing the safety of quiet zones and develop guidance for quiet zone inspections. Implementation of these recommendations may lead to more widespread use of quiet zones.

Other Rail Noise Considerations

Other rail noise challenges include wheel squeal on curves, retarder noise in hump yards, engine idling in yards, and rail crossovers, but these are typically site specific and have been studied and mitigated as such (NAE 2010).

Trains in the United States, including Amtrak's Acela Express, operate at speeds up to 150 mph and are compliant with rail noise standards (40 CFR Part 210). They are not yet operational at higher speeds, but plans are moving forward in the Northeast Corridor, Texas, California, and Nevada for high-speed rail (HSR) operations with anticipated speeds up to 220 mph.[3] It is unclear whether these operations will meet existing noise standards or new standards will need to be considered.

Highway Noise

At highway speeds, noise from vehicles is primarily due to tire/road interaction; engine/exhaust noise tends to be more important at lower vehicle speeds, particularly for trucks. Studies have shown that roadway vehicle noise in the aggregate has varied little over the past 5 decades—automobiles have gotten slightly noisier (likely because of the increase in the number of sport utility vehicles) and trucks slightly quieter at highway speeds (Fleming et al. 1995). As such, there has been very limited research focused on quieting vehicle exterior noise at the source.

Quieter Pavement

While there has been some limited research on quieting vehicle tires (Ögren et al. 2018), most tire/road noise research has focused on quieter pavements (e.g., Anderson et al. 2013; Donavan and Janello 2018; Lodico and Donavan 2018; McGhee et al. 2016). Quieter pavements have also been a focus for reducing roadway noise in national parks, where preserving the natural soundscape is vitally important (Hastings et al. 2020).

Research has shown that some quieter pavements (e.g., open-graded asphaltic concrete) can achieve reductions as large as 10 dB relative to the more common Portland cement concrete and dense graded asphaltic concrete (Donavan and Lodico 2013).

Quieter pavements can reduce roadway noise in national parks, where preserving the natural soundscape is vitally important.

But movement toward the use of quieter pavements in the United States has been slow, for a number of reasons. Trade-offs—in long-term durability, maintenance, and ultimately costs—are a primary consideration (NAE 2010, chapter 7).

Research has shown that the benefits of quieter pavement can deteriorate over time (Anderson et al. 2013; NASEM 2013). The surface can become more compressed, reducing sound-absorbing capacity. The pavement can require additional maintenance and cleaning to retain its sound reduction benefits (PIARC 2013).

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[2] FRA Railroad Crossing Inventory Dashboard, https://railroads.dot.gov/crossing-and-inventory-data/grade-crossing-inventory/crossing-inventory

[3] Information about US HSR initiatives is available at https://railroads.dot.gov/passenger-rail/high-speed-rail/high-speed-rail-timeline.

There are regional dependencies, too; sand and salt used in snowy areas can clog porous sound-absorbing pavements. There have also been practical concerns about establishing quality control/assurance protocols to ensure consistent large-scale installation of quieter pavements (NASEM 2010).

States are understandably reluctant to install quieter pavements that may require more frequent maintenance and overlays—and corresponding lifecycle cost increases. Research on quieter pavements is expected to continue to enhance understanding of the long-term trade-offs. But quieter pavements should be in the toolbox for mitigating highway noise.

Highway Noise Barriers

Given the questions surrounding quieter pavements, most federal/state investment in efforts to reduce highway noise has focused on barriers. Between 1963 and 2016, 3263 linear miles of highway noise barriers were constructed in 48 states and Puerto Rico, at total construction costs of about $7.44 billion—or roughly $34.55/square foot.[4]

> *Research in the 1970s to reduce aircraft fuel burn also led to a marked reduction in aircraft noise.*

To comply with 23 CFR 772, FHWA's Traffic Noise Model (TNM) must be used on all federal-aid highway projects. It has become the de facto standard for predicting noise and designing noise barriers in the vicinity of highways (and can account for some benefits of quieter pavements). FHWA has committed to the advancement of TNM to include the latest science and analytical capabilities, such as improved mapping and integration of a construction noise module in the near future. The FHWA website provides the latest version of TNM (3.0) along with a wealth of related information on highway noise.[5]

[4] FHWA, Summary of Noise Barriers Constructed by December 31, 2016, https://www.fhwa.dot.gov/environment/noise/noise_barriers/inventory/

[5] FHWA, Highway Traffic Noise, https://www.fhwa.dot.gov/environment/noise/

Aircraft Noise

The challenges of commercial aircraft noise date back to at least the early 1950s, with the first flight of the Comet and the dawning of the jet age. With aircraft, it was recognized early on that the traditional approach to analyzing noise probably wasn't adequate. Research by Boeing, the New York Port Authority, and others led to the development of the *tone corrective perceived noise level* and eventually the *effective perceived noise level* (EPNL; Kryter 1960), which is still used for aircraft noise certification.

After the 1970s spike in oil prices, a substantial amount of research was undertaken to reduce aircraft fuel burn. A major outcome of that research, the high-bypass ratio turbofan engine, also resulted in a marked reduction in aircraft noise. As mentioned above, interdependencies (in this case between noise and fuel burn) are a critical factor in understanding transportation noise.

Transport aircraft are certificated according to noise stages; the current one is Stage 5.[6] Modern jet aircraft have achieved a reduction of approximately 15 dB in the average measured EPNL at the three individual certification measurement locations (directly beneath the aircraft on approach, and during takeoff directly beneath as well as off to the side of the aircraft) compared to the first-generation jet aircraft, the Boeing 727s and Douglas DC8s. The corresponding cumulative reduction in certificated EPNL of 40–50 dB represents a cumulative reduction in level at three measurement locations. Figure 2 shows the progress made over the years, and FAA and NASA goals for further noise reduction.

Population Exposure

Another way of looking at progress in reducing aviation noise is in terms of population exposure. In 1975 there were roughly 200 million enplanements; in 2019 there were more than four times that amount—about 935 million. Yet from 1975 to 2019 the population impacted by aircraft noise (measured in terms of the commonly accepted threshold of 65 dB DNL[7]) dropped from 7 million people to about 440,000.

[6] FAA Stage 5 Airplane Noise Standards, https://www.federalregister.gov/documents/2017/10/04/2017-21092/stage-5-airplane-noise-standards

[7] DNL, the day-night average sound level, is the total sound energy over a 24-hour period. It is the principal metric of airport noise.

So there's no longer a problem with aircraft noise, right? Wrong!

Some challenges are technical, but others are more nuanced. The American public is more educated on the topic of aircraft noise, and for those who are adversely affected it is a quality of life issue.

Recent FAA research has shown that people are significantly more sensitive to aircraft noise in general, compared to prior studies.[8] For example, the FAA survey found that, at a noise exposure level of 65 dB DNL, 60–70 percent of people were highly annoyed by aircraft noise, compared with just 12.3 percent 3 decades ago (FICON 1992).

There is also the question of whether the equal-energy principle applies regardless of the level and frequency of the associated events. In other words, would 10 very loud aircraft events result in the same level of public response as 100 moderately loud events, assuming that their cumulative noise energy was equivalent?

One of the more recent technical challenges in aircraft noise is the impact of advanced navigation technology. Precision-based navigation (PBN) and area navigation of aircraft enabled by geographic positioning systems (GPS) have many benefits, including, importantly, improved safety through reductions in pilot and air traffic controller workload.

But some of the other benefits of PBN—fuel savings, time savings, and congestion reduction—entail tradeoffs. Figure 3 shows aircraft flight tracks at Boston's Logan International Airport before and after the implementation of PBN. It does not take an acoustician to conclude that the noise impacts on the ground have changed: fewer people are impacted since implementation of PBN, but those beneath these superhighways in the sky probably experience an increase in noise from the concentrated overflights. These heavily trafficked skyways may also raise equity issues. Trying to assess the impacts of PBN-related changes is a challenge for both airports and the FAA.

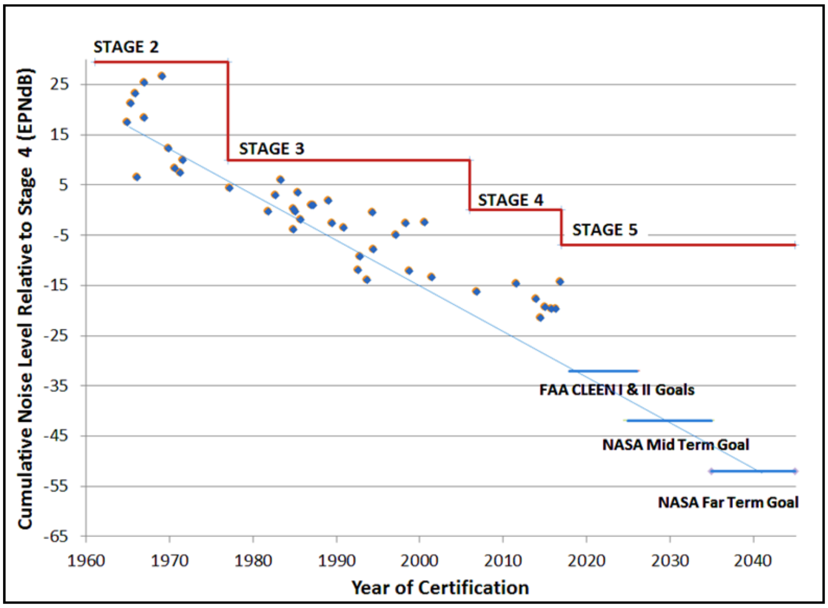

FIGURE 2 Aircraft noise certification values, 1960–2040. CLEEN = Continuous Lower Energy, Emissions, and Noise program. Reprinted from INCE-USA (2017).

Federal Initiatives

The FAA, NASA, and their partners support efforts in the following areas to better understand and improve the aviation noise soundscape: (i) better modeling capabilities; (ii) studies of noise and its impacts on public annoyance, sleep, learning, and health; (iii) community outreach, including education tools; (iv) research supporting noise reduction at the source; and (v) noise mitigation through operational procedures and sound insulation at sensitive receptors.

Initiatives include the continued advancement of FAA's Aviation Environmental Design Tool (AEDT),[9] Center of Excellence for Alternative Jet Fuels and Environment (ASCENT),[10] and Continuous Lower Energy, Emissions and Noise (CLEEN) Program[11]; and NASA's Aeronautics Research Program.[12]

AEDT is the de facto standard for modeling aircraft noise in the vicinity of airports. Its development is supported in part by research initiatives of ASCENT, which is an FAA partnership with NASA, EPA, the Air Force Research Lab, Department of Agriculture, Department of Energy, Defense Logistics Agency, Transport

[8] FAA, Neighborhood Environmental Survey (as of Jan 12, 2021), https://www.faa.gov/regulations_policies/policy_guidance/noise/survey/

[9] https://aedt.faa.gov/

[10] https://ascent.aero/topic/noise/

[11] https://www.faa.gov/about/office_org/headquarters_offices/apl/research/aircraft_technology/cleen/

[12] https://www.nasa.gov/aeroresearch

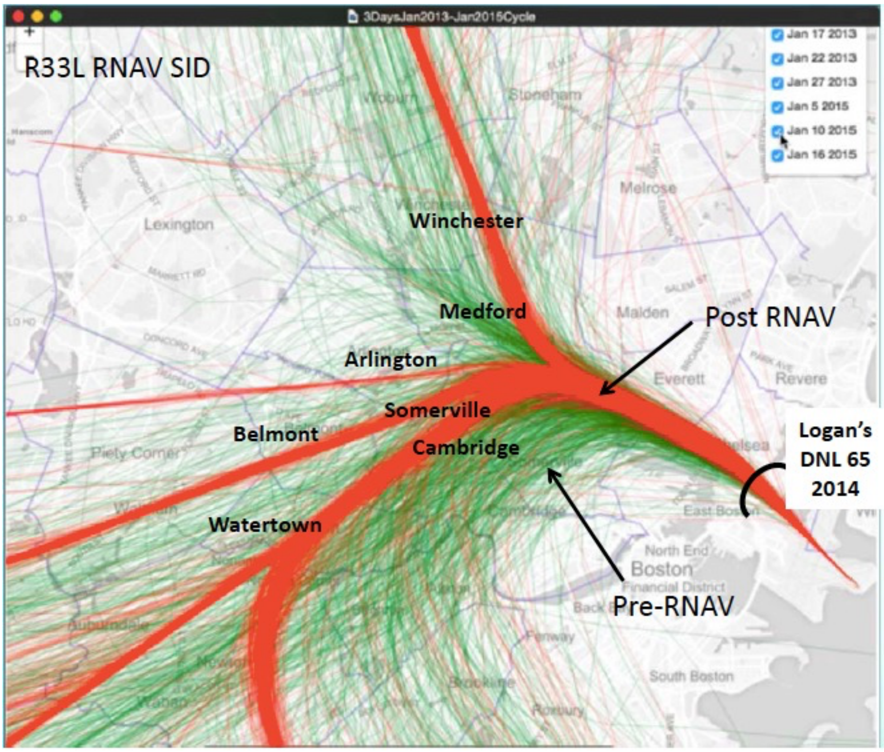

FIGURE 3 Aircraft ground tracks before (green) and after (red) implementation of precision-based area navigation (RNAV) at Boston's Logan Airport. Reprinted from INCE-USA (2017).

Canada, a consortium of seven universities, and a range of industry partners. CLEEN is a public-private partnership closely coordinated with NASA and including a number of aerospace industry contributors.

Because aviation noise is a challenge for a number of federal agencies, the Federal Interagency Committee on Aviation Noise[13] was established in 1993 to "assist agencies in providing adequate forums for discussion of public and private sector proposals, identifying needed research, and in encouraging the conduct of research and development in these areas."

Helicopter Noise

Helicopter noise is particularly prevalent in urban areas such as New York, Los Angeles, Chicago, and Washington (GAO 2021) as well as cities near the Gulf of Mexico (associated with oil rig access). It is also a concern in national parks (along with noise from other small, tour aircraft).

Community engagement on the subject of helicopter noise often involves noise levels lower than those of fixed-wing aircraft, but concerns are due to the different nature of the sound. Rotary-wing noise has therefore been a focus of the FAA, NASA, and Department of Defense, particularly in research to reduce source noise. The Helicopter Association International has launched the Fly Neighborly initiative, "a voluntary noise reduction program that seeks to create better relationships between communities and helicopter operators by establishing noise mitigation techniques and increasing effective communication."[14]

Looking Forward

It is unclear how the covid-19 pandemic will affect the US and global transportation landscape. Will the demand for business air travel be permanently reduced through new platforms like video conferencing? Will rail transit return to prepandemic levels? How will the shift to a more remote workforce impact highway congestion, and transportation demand more broadly? No one knows the answers to these questions and speculation is well beyond the scope of this article.

Independent of the impacts of the covid-19 pandemic, following are major anticipated trends in transportation noise:

- *Promotion and implementation of quiet zones, including train horn noise mitigation strategies, will continue in the vicinity of rail-grade crossings.* Also, once operational in the United States, HSR is expected to lead to new noise challenges that will require research and new policies and regulations.
- *Research into quieter pavements will continue, to complement highway noise reductions achieved by noise barriers.* In addition, substantial investment in vehicle charging stations across the country is expected to facilitate greater use of electric vehicles.[15] Hybrid technology will also likely become more pervasive (the path

[13] https://fican.org

[14] https://www.rotor.org/initiatives/fly-neighborly

[15] FAA Alternative Fuel Corridors, https://www.fhwa.dot.gov/environment/alternative_fuel_corridors/

to hydrogen-powered vehicles is less clear). These technologies will help reduce noise on roadways, but mostly at lower speeds where tire/road noise is less pronounced. Furthermore, these technologies can have unintended consequences for safety, particularly for the visually impaired at lower speeds, and these must be considered (Garay-Vega et al. 2010).

- *Continued research in aviation-related source noise reduction, including (i) traditional large-passenger tube-and-wing designs; (ii) advanced concept airframes and propulsion systems for large cargo and passenger aircraft (e.g., blended-wing body, electric, and potentially hydrogen); and (iii) drones, advanced air mobility (AAM), helicopters, and commercial space vehicles*. While safety must remain the priority, reductions in aviation noise will likely need to be commensurate with significant reductions in fuel burn, given concerns about climate change and the substantial cost of aircraft fuel. Electric aircraft offer important potential benefits in terms of noise and energy use, but their mission capabilities are expected to be very limited. There are widely differing views on the future of hydrogen propulsion technology for aircraft. It is expected that there will be a resurgence in commercial supersonic flight, but for at least the next decade such flights will likely be limited to overwater routes. NASA, in cooperation with the FAA and others, is designing and building a low-boom supersonic demonstrator to assess its acceptability in overland flight.[16]

While vehicle automation[17] will provide societal benefits, care must be taken to mitigate unintended consequences such as the potential for increased noise due to more freely flowing highway traffic and expected growth in drone and AAM operations.[18] Workshops on drone and AAM noise in 2018 and 2020 (INCE-USA 2020) highlighted the many noise-related considerations associated with the rapidly increasing demand for these new technologies. On the positive side, roadway vehicle automation could eventually yield noise benefits such as omission of the need for train horns. Likewise, cargo delivery drones may reduce the use of ground-based vehicles, potentially resulting in noise benefits, or maybe just changing the nature of the noise experience for the public.

In addition, there needs to be more consideration of transportation noise in the aggregate—rail, highway, and aircraft and both traditional and autonomous vehicles. The BTS-led transportation noise mapping initiative is an excellent step in that direction. Also, more consolidation of noise prediction models (e.g., the planned integration of a construction noise module in TNM) will help. And with the anticipated growth of HSR in the United States, why not a rail noise module in TNM?

But updating noise models to consider multimodal contributions is not enough. It does not make sense to design noise barriers along an interstate near a runway without considering the aircraft noise, or to make residential insulation decisions about aviation noise impact for a community adjacent to an interstate without considering the noise from the latter.

Electric vehicles and hybrid technology will help reduce noise on roadways, but mostly at lower speeds.

Integrated models will help inform approaches in these situations, but it is also necessary to consider the adequacy of modally based transportation-related noise policies and land-use planning guidance. What impact will FAA's 2021 survey have on aviation noise policy? Might it affect the noise policies of other modes? Time will tell!

Conclusions

There has been much progress in reducing transportation-related noise. But there is still more to do. Some challenges are technical, but in many cases they are related to willingness, awareness, and trade-offs.

What's needed is sustained, coordinated, and arguably greater attention to transportation-related noise in the United States. All the tools in the proverbial toolbox must be used to ensure that—with expected population growth and related increased demand for transportation as well as new modes of movement (e.g., drones, autonomous vehicles)—the transportation noise landscape at least maintains the status quo and, ideally, improves.

[16] NASA low-boom flight demonstration, https://www.nasa.gov/X59

[17] USDOT Intelligent Transportation Systems Joint Program Office: ITS Research Automation, https://www.its.dot.gov/research_areas/automation.htm

[18] FAA, Unmanned Aircraft Systems, https://www.faa.gov/uas

Acknowledgments

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References

Anderson K, Uhlmeyer JS, Sexton T, Russell M, Weston J. 2013. Evaluation of Long-Term Pavement Performance and Noise Characteristics of Open-Graded Friction Courses Project 3 – Final Report. Olympia: Washington State Department of Transportation.

Donavan P, Janello C. 2018. Arizona Quiet Pavement Pilot Program: Comprehensive Report. Phoenix: Arizona Department of Transportation.

Donavan PR, Lodico DM. 2013. Influence of quieter pavement and absorptive barriers on US-101 in Marin County, California. Transportation Research Record 2362(1):25–34.

FICON [Federal Interagency Committee on Noise]. 1992. Federal Agency Review of Selected Airport Noise Analysis Issues. Washington.

Fleming GG, Rapoza AS, Lee CSY. 1995. Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model (FHWA TNM), version 1.0. McLean VA: Federal Highway Administration.

FRA [Federal Railroad Administration]. 2013. Guide to the quiet zone establishment process. Washington.

GAO [Government Accountability Office]. 2017. Railroad Safety: Quiet Zone Analyses and Inspections Could Be Improved (GAO-18-97). Washington.

GAO. 2021. Aircraft Noise: Better Information Sharing Could Improve Responses to Washington, DC Area Helicopter Noise Concerns (GAO-21-200). Washington.

Garay-Vega L, Hastings A, Pollard JK, Zuschlag M, Stearns MD. 2010. Quieter Cars and the Safety of Blind Pedestrians: Phase 1. Washington: National Highway Traffic Safety Administration.

Hastings AL, Rapoza AS, Kaye S, Flynn D. 2020. Quieter Pavement Project – Death Valley National Park: Interim report for one-year post-treatment conditions. Ft Collins CO: National Park Service.

Hummer JE, Jafari MR. 2007. Railroad Crossing Wayside Horn Evaluation. Raleigh: North Carolina Department of Transportation.

INCE-USA [Institute of Noise Control Engineering of the USA]. 2017. Engineering a Quieter America: Commercial Aviation: A New Era. Reston VA.

INCE-USA. 2020. Engineering a Quieter America: UAS and UAV (Drone) Noise Emissions and Noise Control Engineering Technology. Reston VA.

Janssen SA, Vos H. 2011. Dose-response relationship between DNL and aircraft noise annoyance: Contribution of TNO (DOT/FAA/AEE/2011-04). The Hague: Netherlands Organisation for Applied Scientific Research.

Kryter KD. 1960. The meaning and measurement of perceived noise level. Noise Control 6(12).

Lodico D, Donavan P. 2018. Quieter Pavement: Acoustic Measurement and Performance. Sacramento: California Department of Transportation.

Lucke RE, Raub RA. 2004. Use of automated wayside horns for improving highway-rail grade crossing safety. Proceedings, ITE Annual Mtg and Exhibit, Aug 1–4, Lake Buena Vista FL.

Lucke RE, Raub RA, Thunder TE. 2012. Improving road safety and residential quality of life. Applied Health Economics and Health Policy 3:71–78.

McGhee KK, De León Izeppi ED, Flintsch GW, Mogrovejo DE. 2016. Virginia quieter pavement demonstration program. Transportation Research Record 2571(1):49–58.

Multer J, Rapoza A. 1998. Field Evaluation of a Wayside Horn at a Highway-Railroad Grade Crossing. Washington: Federal Railroad Administration.

NAE [National Academy of Engineering]. 2010. Technology for a Quieter America. Washington: National Academies Press.

NASEM [National Academies of Sciences, Engineering, and Medicine]. 2010. 2008 Survey of European Composite Pavements. Washington: National Academies Press.

NASEM. 2013. Evaluating Pavement Strategies and Barriers for Noise Mitigation. Washington: National Academies Press.

Ögren M, Molnár P, Barregard L. 2018. Road traffic noise abatement scenarios in Gothenburg 2015–2035. Environmental Research 164:516–21.

PIARC [World Road Association]. 2013. Quiet Pavement Technologies (2013R10EN). Paris.

Regularly updated national and international noise standards ensure consistency and accuracy among products.

Voluntary National and International Noise Standards for Products and Machines

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Voluntary noise standards, which are developed by consensus-based standards organizations, define reliable and reproducible procedures to ensure that manufacturers (i) design their products to meet customer, market, and/or regulatory requirements; (ii) get components that meet their specifications; and (iii) report noise values that are measured in the same way as their competitors so that purchasers can trust values of product noise levels given by manufacturers. The use of these standards can lead to quieter products resulting in better working conditions, quality of life, and worker health as well as competitive advantages.

The importance of measurement standards was summarized by William Thomson, Lord Kelvin (1891, p. 80):

- "To measure is to know."
- "If you cannot measure it, you cannot improve it."
- "When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind."

Product Noise Metrics

There are two different aspects of product noise: the noise emitted by a product and the noise measured from a product in situ.

The primary descriptor of the noise emitted by a product is the *sound power level,* supplemented by the *emission sound pressure level* at an operator position. Both are independent of the environment in which the product is located. These sound levels are important for design purposes and, when using psychoacoustic standards, for evaluating annoying aspects of product sounds (e.g., prominent discrete tones, roughness). The product sound power level can be used to compare the noise of different manufacturers' products, such as computers, dishwashers, and manufacturing machinery.

Sound levels are important for design purposes and, when using psychoacoustic standards, for evaluating annoying aspects of product sounds.

The descriptor of the sound that is produced from a product measured in its installed location is the *in situ sound pressure level*, which takes into account the effects of where the source is located and sound reflections from walls. The in situ sound pressure level is a descriptor for the sounds heard by persons, whether users, bystanders, or community.

The sound power level is measured in decibels (dB) relative to 1 picowatt and the sound pressure level is measured in dB relative to 20 micropascals. For most products the two sound levels are A-weighted; that is, the sounds are frequency weighted according to the A-weighting curve, which approximates human hearing for midlevel sounds, and reported in dBA.

Standards Organizations

Many US and international organizations develop acoustical and noise standards.

The American National Standards Institute (ANSI) has accredited standards committees (ASCs) on acoustics, bioacoustics, mechanical vibration and shock, and noise, all administered by the Acoustical Society of America (ASA). Founded in 1929, ASA sponsored the development of acoustical standards through its committee on Acoustical Standardization (Blaeser and Struck 2019). And standardization has remained important to ASA, as demonstrated by the fact that six ASA presidents and two vice presidents have been the society's standards leaders or directors (four of the leaders were also NAE members).

Other ANSI-accredited standards organizations with acoustical or noise standards include the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE), ASTM International (formerly known as the American Society for Testing and Materials), American Society of Mechanical Engineers (ASME), Air Conditioning, Heating, and Refrigeration Institute (AHRI), and SAE International (formerly the Society of Automotive Engineers). George Maling (2021) in this issue further discusses various organizations with acoustical or noise standards.

The International Organization for Standardization (ISO) has relevant technical committees (TCs) and subcommittees (SCs), including TC43 (Acoustics) and TC43/SC1 (Noise). Some ISO standards are the basic acoustic standards for the measurement of product and equipment noise.

The International Electrotechnical Commission (IEC) develops standards for acoustical instruments as well as electrical, electronic, and related technologies, including acoustical measurement instruments, household appliances, and wind turbines.

Basic Standards for Measuring Product and Equipment Noise

Basic product acoustic standards include criteria for measuring noise from various types of products and machinery and outline general mounting and operating conditions. Product-specific standards use the basic standards that have the type of measurement and the grade of measurement uncertainty desired. Grades of measurement uncertainty are characterized as precision (class 1), engineering (class 2), and survey (class 3). Product-specific standards also define product mounting and operating conditions and operator position for measuring the emission sound pressure level.

ISO basic sound power level and emission sound pressure level standards were developed beginning in the early 1970s. William W. Lang (NAE), leader of the ISO subgroup and then chair of the working group that developed these standards, recognized the need for effective, reliable, and uniform measurement procedures.

For Measuring Sound Power Levels

There are two sets of ISO basic product standards for the determination of sound power levels:

- ISO 3741 to 3747 (using sound pressure level measurements) (the US adoptions of these ISO standards are the ANSI/ASA S12.51–S12.57 series)
- ISO 9614-1 to 9614-3 (using sound intensity measurements) (the US sound intensity standard is ANSI/ASA S12.12).

The procedures in ISO 3744, 3747, and 9614-2 meet engineering-grade accuracy, which is advantageous to manufacturers, and especially for legal requirements; ISO 3741, 3745, and 9614-3 meet precision-grade accuracy.

The ISO 3741–3747 series provides for measurements in reverberant test rooms and fields, anechoic chambers, hemi-anechoic chambers (rooms with anechoic properties above a reflecting plane), essentially free-field over a reflecting plane, and in situ in a reverberant environment. ISO standards also provide criteria for qualifying anechoic and hemi-anechoic chambers.

ISO 3744 (engineering grade) is the most commonly used basic product noise standard in product-specific standards and is referenced in several European Commission regulations and test procedures. It is under revision to simplify the methods and procedures and to remove most of the provisions for determining environmental correction factors, which will go into a separate updated ISO standard

ISO 9295 specifies methods for the determination of sound power levels in the high-frequency range. It could serve as the basis for standards to measure frequencies for products that emit ultrasound, such as some medical devices.

ISO sound intensity standards for determining sound power levels include significant requirements on stationary background noise and other factors that make them more difficult to perform reproducibly. But sound intensity measurements are a valuable tool for testing products that are too large for the test spaces in the ISO 3741–3747 series and for locating specific sources of noise in a product, supplemented by knowledge of the product operating conditions.

For Measuring Emission Sound Pressure Levels

The ISO basic product standards for determining emission sound pressure levels (ISO 11201–11205) have different grades of accuracy. Their methods involve using (i) measurements in a free field over a reflective plane with negligible, approximate, or accurate environmental corrections; (ii) calculations from the sound power level; and (iii) sound intensity measurements.

For Declaring Product and Equipment Sound Levels

The ISO basic product acoustic standard for declaring (or publishing) product and equipment sound levels (ISO 4871) calls for either adding uncertainty to the measured values for a "guaranteed" level or reporting the measured value and the uncertainty.

An ISO standard may be used to measure frequencies for products that emit ultrasound, such as some medical devices.

The newly approved US standard for declaring product sound levels (ANSI/ASA 12.61:2020) uses a different approach to achieve the same results. The mean measured value is always reported, and the uncertainty is optionally reported (e.g., when required by regulatory authorities). If the uncertainty value is not reported, methods of verifying the declared levels are given.

Other Acoustic and Noise Standards Related to Product Noise

An ISO standard (9613-2, attenuation of outdoor sound propagation) predicts the equivalent continuous A-weighted sound pressure level under various meteorological, terrain, vegetation, and barrier conditions. Software programs implement the calculation methods of this standard to predict sound pressure levels in communities from sound power levels of sources such as wind turbines, emergency generators, and transformers.

ANSI/ASA S12.2 provides three methods for evaluating room noise: a survey method that employs the in situ A-weighted sound pressure level, an engineering method that uses expanded noise criteria (NC) curves, and a method for evaluating low-frequency fluctuating noise that uses room noise criterion (RNC) curves. An informative annex to this standard gives recommended noise level criteria for various occupied activity areas; for example, the A-weighted sound pressure level criteria for classrooms are the same as the maximum one-hour sound levels in ANSI/ASA S12.60 (Parts 1 and 2) for classroom acoustics. Product manufacturers can use these criteria to determine sound power levels for the activity areas in which the products will be located.

Product-Specific Noise Standards

Information Technology Products

In the 1970s the information technology (IT) industry recognized noise as a factor in both customer acceptability and possible government regulations. International IT noise standards were created by industry, government, and users based on standards developed by American and European industry trade associations in cooperation with ASA standards committees. ANSI S1.29-1979 became the basis for the Ecma International[1] standard ECMA-74, which was the basis for ISO 7779.

The IT industry recognizes noise as a factor in both customer acceptability and possible government regulations.

ISO 7779 and ECMA-74—both used worldwide and cited in European directives and regulations—include product-specific operating and mounting conditions for A-weighted sound power and sound pressure levels. The US equivalent is ANSI/ASA S12.10/Part 1.

New IT products are introduced regularly, of course, and operating modes may change as products evolve, so it is necessary to frequently revise these standards. Because the revision cycle for ECMA-74 is considerably shorter than for ISO revisions, ISO 7779 now refers to product mounting and operating conditions in the current edition of ECMA-74.

The IT industry also has standards for declared noise levels: ISO 9296 and its more up-to-date counterpart ECMA-109 (10th edition), which has methods similar to ANSI/ASA S12.61.

The IT industry also developed standards for determining air- and structure-borne sound power levels from small fans (ISO 10302-1/ECMA-275-1 and ISO 10302-2/ECMA 275-2, respectively). A fan mounted on a special acoustically "transparent" plenum can operate under pressure loading conditions similar to those when installed in computer systems. The previous noise descriptor for fans—an emission sound pressure level under no load conditions—was not useful for selecting fans used in computer products.

The German Environment Agency Blue Angel[2] is an environmental label ("The German Eco-Label") for many product types. Its noise criterion is the A-weighted sound power level, and for IT equipment it is measured according to ISO 7779 and reported according to ISO 9296. The Blue Angel sound power level criterion for desktop computers in 2015 was 10–13 dBA lower than in 1995, and there was a similar reduction in measured product sound power levels, reductions that may be attributed to energy efficiencies, source noise control techniques, enclosure designs—and uniform worldwide measurement and declaration standards (Beltman 2016).

Household Appliances

There are numerous product-specific IEC noise standards for household appliances and similar devices (IEC 62704-1, -2, and -3 series). For some, the A-weighted sound power level methods are based on ISO 3744 with product-specific operating and mounting conditions; the declaration standard is based on ISO 4871. The European Commission requires appliances' energy labels to display the declared A-weighted sound power level determined according to these IEC standards.

Wind Turbines

Large wind turbines emit sound power levels characterized by modulation and "swooshing." The IEC 61400-11 standard "Wind turbine acoustic noise measurement techniques" specifies methods to determine A-weighted sound power levels. Sound pressure levels are measured at a single microphone location and hemispherical spreading is assumed to determine the sound power levels as a function of wind turbine electrical output power.

[1] Formerly the European Computer Manufacturers Association

[2] https://www.blauer-engel.de/en/our-label-environment

The IEC wind turbine sound power level values are used as input data for computer programs (based on ISO 9613-2) that predict energy-equivalent sound pressure levels at residential receptors. Experience has shown good agreement between predicted and measured wind turbine energy-equivalent sound pressure levels with the appropriate selection of ground factors and other settings in the programs (Kaliski et al. 2018). In many communities and states the criteria for approval of the installation of wind turbines require predictions of sound pressure levels using programs based on ISO 9613-2.

Other Product Types

The uses and applications of noise measurement standards described suggest opportunities for the use of such standards for other types of products.

Small Unmanned Aircraft Systems: Drones

Small unmanned aircraft systems (UAS) are regulated in the United States by the Federal Aviation Administration. It has been suggested, based on the experience of the IT and wind turbine industries, that the A-weighted sound power level may be suitable to quantify small drone noise emissions (Hellweg and Maling 2020), an approach that has the following advantages:

- Different measurement methods may be used and can be taken indoors or outdoors.
- Sound power levels can meet the needs of manufacturers, users, the public, and governments.
- Community sound pressure levels can be predicted from the sound power levels.

Implementation of this suggestion requires selecting a method to determine sound power levels for various operating modes.

The ASC S12 (Noise) Working Group 58 is developing an ANSI/ASA standard to determine the A-weighted sound power level of small UAS (less than 25 kg) in an anechoic room and is also considering outdoor measurements.

The European Commission (2019) enacted a delegated regulation on small UAS that requires measuring and publishing A-weighted sound power levels according to ISO 3744. It also sets limits on maximum A-weighted sound power levels for small UAS of 0.25–4 kg.

A joint working group WG7 of ISO TC20/SC16 (Unmanned Aircraft Systems) and ISO TC43/SC1 (Noise) has begun development of a standard for noise measurements of small multirotor UAS.

Hand Dryers

A recent study of hand dryers showed that A-weighted sound pressure levels measured in situ are both very loud and significantly noisier when hands are in the airstream (Keegan 2020a).

A recent study showed that hand dryers are both very loud and significantly noisier when hands are in the airstream.

At least one manufacturer's laboratory measured noise without the effect of hands in the airstream and did not measure the operator position sound pressure level, only the sound power level (Keegan 2020b). The manufacturer said it could not measure at the operator position because the device was tested on the floor of a hemi-anechoic chamber. ISO standards require that equipment designed to be operated on a wall be installed on a wall for measuring operator position sound pressure levels, since there are reflections from both the wall and the reflecting surface in the test room.

ISO standards also require testing in a mode "representative of the noisiest operation in typical usage," so the operating mode of hand dryers during acoustic tests should simulate hand interference.

Experience indicates that it is practicable to measure the operator position of wall-mounted IT products on a portable wall in a hemi-anechoic chamber to meet ISO requirements.

Psychoacoustic Standards

Psychoacoustic standards can help manufacturers understand how their products will be perceived by users in order to reduce annoying aspects of product noise during design. Psychoacoustic parameters used to define the perception of noise include loudness, prominent tones and tonality, and roughness.

Loudness

There are two ISO standards with methods for calculating loudness and a third under development:

- ISO 532-1: Part 1: Zwicker method
- ISO 532-2: Part 2: Moore-Glasberg method
- ISO/AWI 532-3 (under development): Part 3: Moore-Glasberg-Schlittenlacher method for time-varying sounds.

The ANSI/ASA S3.4 loudness standard is similar to ISO 532-2, and includes a software program.

Prominent Tones and Tonality

If a product's noise has tonal components that are several decibels above noticeability and are deemed to be prominent, the noise emissions could be annoying depending on other background sounds. Several product-specific standards have methods for the measurement of prominent discrete tones or tonality.

IT Industry

The IT industry has three methods each using narrow-band fast Fourier transform (FFT) analyses: two for prominent discrete tones and one for prominent tonality. Some IT developers also use narrow-band data to identify the source of unwanted sounds in their products. Several IT manufacturers have criteria on prominent discrete tones in their purchase specifications for components (e.g., hard disk drives and fans).

Some IT developers use narrow-band data to identify the source of unwanted sounds in their products.

The newest standards on tonality are ECMA-418 psychoacoustic metrics for IT equipment: Part 1 for prominent discrete tones and Part 2 for models based on human perception. ECMA-418-1 replaces and updates technical content with methods to determine the tone-to-noise ratio and the prominence ratio, and ECMA-418-2 provides a prominent tonality method based on a hearing model (Sottek 2016).

Wind Turbines

The IEC 61704-11 standard uses an FFT method to evaluate tonality from sound pressure level measurements to determine sound power levels.

Others

Other procedures evaluate tonal components for general or environmental evaluations of product noise in situ or in laboratories. The ISO/PAS 20065 publicly available specification uses a narrow-band FFT method to determine the audibility and prominence of tones in noise. It is being revised as a technical specification to eventually become an international standard. Its methods are used in ISO 1996-2, "Determination of environmental sound pressure levels," to determine audibility and prominence of tones in environmental noise.

Roughness

ECMA 418-2 uses a method based on the hearing model (Sottek 2016) to determine roughness and whether it is prominent.

Summary

Noise standards are important in the development of quiet products and are referenced in national and international regulations to ensure uniformity of measurements and to avoid conflicting methods. Used by manufacturers, purchasers, and governments, they are continually assessed and should be updated to respond in a timely and responsible manner to new product types, technologies, and capabilities. Noise control engineers are instrumental in the development and implementation of such standards to reduce harmful noise impacts and enhance quality of life.

References

Beltman M. 2016. Experience with noise emission declarations and labels: Information technology industry. Buy Quiet Symposium, International INCE, Aug 25, Hamburg.

Blaeser S, Struck CJ. 2019. A history of ASA standards. Journal of the Acoustical Society of America 145(1):77–109.

European Commission. 2019. Delegated Regulation (EU) 2019/945 of 12 March 2019 on unmanned aircraft systems and on third-country operators of unmanned aircraft systems. Official Journal of the European Union 62(L 152).

Hellweg RD Jr, Maling GC Jr. 2020. Noise regulation: Federal standards or self-certification by the private sector? In: Engineering a Quieter America: UAS and UAV (Drone) Noise Emissions and Noise Control Engineering Technology. Reston VA: INCE-USA.

Kaliski K, Bastasch M, O'Neal R. 2018. Regulating and predicting wind turbine sound in the US. Proceedings, INTER-NOISE 2018, Aug 26–29, Chicago.

Keegan NL. 2020a. Children who say hand dryers "hurt my ears" are correct: A real-world study examining the loudness of automated hand dryers in public places. Paediatrics & Child Health 25(4):216–21.

Keegan N. 2020b. Hair dryer noise: Identifying the problem and proposing a solution. Plenary lecture, NOISE-CON 2020, Nov 16–20 (online).

Maling GC Jr. 2021. Resources for noise control engineering. The Bridge 51(2):41–47.

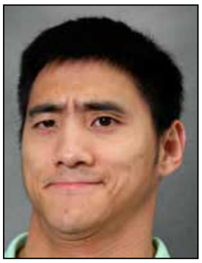
Sottek R. 2016. A hearing model approach to time-varying loudness. Acta Acustica united with Acustica 102(4):725–44.

Thomson W. 1891. Popular Lectures and Addresses, Vol I. London: MacMillan.

Advances are needed to enhance the accuracy and application of acoustic source localization techniques.

Acoustic Source Localization Techniques and Their Applications

Yangfan Liu, J. Stuart Bolton, and Patricia Davies



Yangfan Liu

Stuart Bolton

Patricia Davies

Acoustic source localization technology is used to determine the location(s) of a sound source or multiple sources in an environment by processing acoustic signals measured at a number of locations.[1] Many techniques are capable of not only localizing but also estimating sound source types and strengths, information that can then be used to predict the sound field everywhere in the environment. With this information, for example, it is possible to generate a visual representation of the sound sources and sound field distribution in a region of interest and virtually recreate the sound that would be heard at any location in the environment.

[1] Depending on specific applications, methods may be denoted with different terms (e.g., sound source visualization, sound field reconstruction or visualization) and acoustic array techniques.

Yangfan Liu is an assistant professor and Stuart Bolton a professor in the Department of Mechanical Engineering, where Patricia Davies is also a professor as well as former director of Ray W. Herrick Laboratories, all at Purdue University.

In this article, we discuss techniques of acoustic source localization, challenges, and potential applications of both the source and sound field information.

Introduction

The very first application of acoustical source localization appeared more than 100 years ago, with the invention of "acoustic telescopes" to detect ships in foggy weather. An example of early sound source localization devices is shown in figure 1. The idea is that if the device is facing in the direction of a sound source, sounds collected at receivers arrive simultaneously and so reinforce each other when the mixed sound is heard.

Although more sophisticated localization techniques are available today, the phase reinforcement principle still commonly underlies modern localization devices. The need to mechanically rotate the device to search for directions of phase reinforcement led to signal processing of the sound measured at fixed microphone locations (figure 2) to recreate the effect of rotation without the need to actually move the array.

Acoustic source localization has been used not only for ship and vehicle detection but also location of dominant noise sources in machines (e.g., engines, vehicles, airplanes) to guide product noise control, target selection and interference rejection for communication devices or speech recognition processing, and condition monitoring for mechanical systems.

Furthermore, with the ability to estimate source strengths and the resulting sound field, localization approaches have been widely implemented in the acoustical design of audio devices and theater systems, noncontact measurements of vibration, and audio virtual reality systems, among other uses. With recent advances in machine learning, cloud computing, and on-chip electronics, acoustic source localization techniques are finding their future in an ever wider range of applications.

Acoustic Source Localization Techniques

There are two main types of acoustical visualization techniques: beamforming and holography. Generally speaking, beamforming focuses on finding source locations and holography on predicting sound fields.

In beamforming, sources are found by scanning all potential source locations and then determining how likely an actual source is at each potential location based on the strength of the combined microphones' output signals.

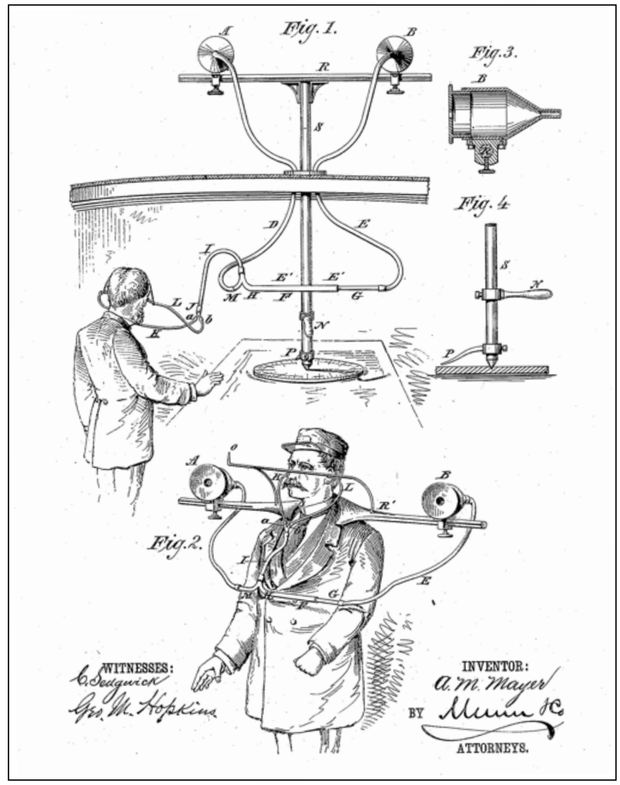


FIGURE 1 Early acoustic source localization device: Mayer telescope in 1880, US patent number 224199.

FIGURE 2 Typical modern microphone array for acoustic source localization. This array features 36 microphones and is being used to identify noise source locations on the front of a diesel engine. Photograph courtesy of Tongyang Shi.

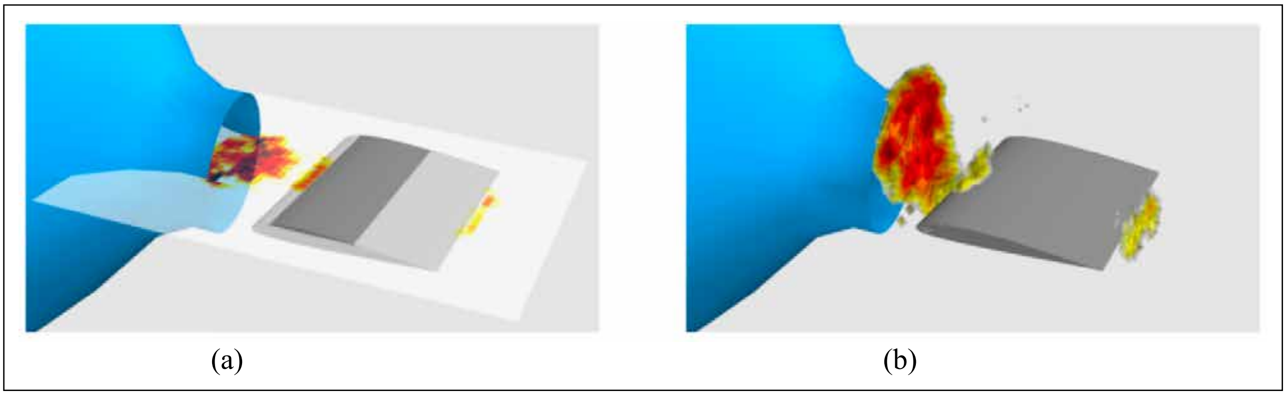


FIGURE 3 Example of beamforming source localization result for jet noise around air foil: (a) 2D scan, (b) 3D scan. Reprinted from Geyer et al. (2012).

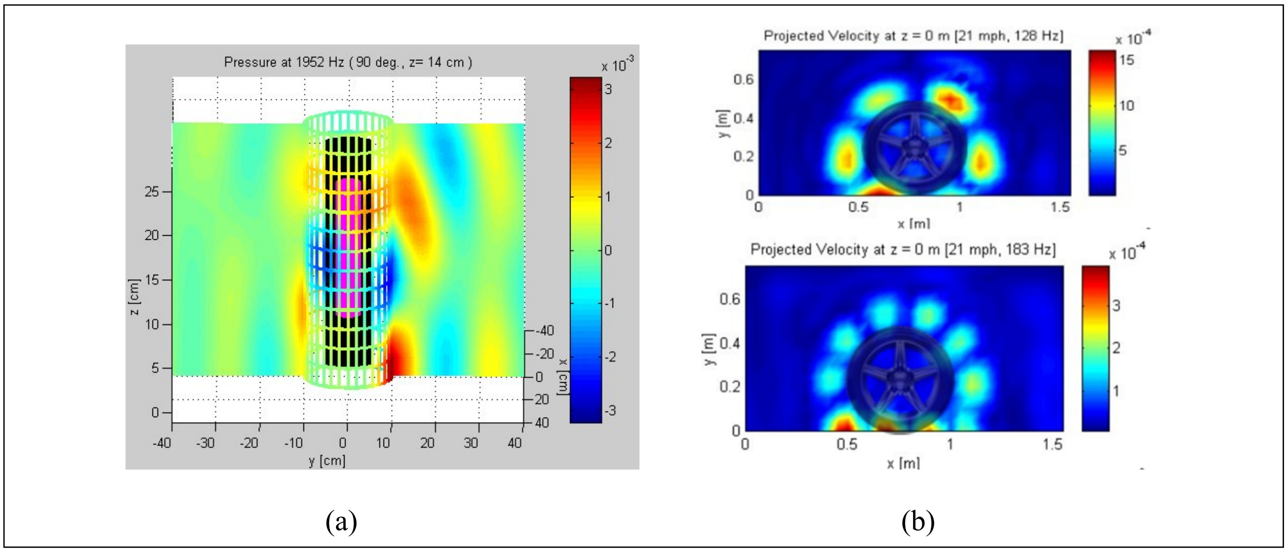


FIGURE 4 Examples of acoustical holography source field visualization results: (a) sound pressure radiation from a refrigeration compressor; (b) holographic visualization of surface vibration of a rolling tire (showing different modal patterns for different resonance frequencies). Author's images (JSB).

In acoustical holography, sources are assumed to exist at all potential locations at the same time; the strength of each potential source is estimated by finding the best match to measurements. Once the source strengths are calculated, the sound field can be predicted by solving a straightforward sound propagation problem.

Examples of source localization and sound field visualization results from beamforming and acoustical holography are shown in figures 3 and 4. In figure 3, the red indicates locations where sound is generated by flow turbulence and interaction of the flow with the solid surface of an airfoil. Figure 4(a) shows sound radiating away from a refrigeration compressor; the red and blue designate the locations of positive and negative sound pressures (respectively) at one instant of time. Figure 4(b), showing the surface motion of the sidewall of a rotating tire at two different frequencies, clearly indicates the standing wave patterns that form in a rolling tire.

Acoustical Beamforming

The earliest microphone array beamforming technique, dating from the 1940s (e.g., Dolph 1946), is called *delay-and-sum* processing, which implements a principle similar to the mechanical localization devices mentioned above.

After assuming a "look" direction, the relative time differences due to sound propagation between each microphone signal and the signal at a chosen reference microphone can be determined. The likelihood of an actual source in the assumed look direction is calculated by delaying (or compensating for) the relative time differences at all microphones on the array, and then summing them up.

If the look direction coincides with the actual source direction, signals at all microphones will be in phase with the reference microphone signal, and thus reinforce and result in a strong total signal. When the look direction differs from the actual source direction, the signals will not be in phase, and the mutual cancellation will produce a weak output signal (Johnson and Dudgeon 1992).

Many more advanced beamforming techniques have since been developed. They mainly differ in the choice of the performance criteria to be maximized or minimized (Chiariotti et al. 2019). Mathematically, the traditional delay-and-sum technique minimizes the source strength prediction error in the assumed look direction (or location) and thus ensures that the beamforming produces the best prediction when the look direction is "correct."

A variant of the beamforming technique, the minimum variance distortionless response method, imposes a constraint that requires it to output the exact (or distortionless) source strength when the look location is "correct." At the same time, it minimizes the total output signal power, so the response when the look direction is "wrong" is minimized.

Another variant, the linear constraint, minimum variance beamforming method, places further constraints on the formulation: it guarantees, for example, zero response to sources at known locations or sound from known reflecting surfaces, which can further remove interference caused by previously known sources.

Acoustical Holography

Acoustical holography methods usually aim to predict the sound field at an arbitrary location based on acoustical measurements at a number of locations (i.e., at the array microphones), rather than identifying only a source direction. Almost all holography techniques rely on the use of a number of basic virtual sources to represent any possible sound field in the prediction region. The undetermined source strengths and other parameters are estimated by minimizing the discrepancy between the predicted sound field and the measured sound field at the microphone locations.

Acoustical holography methods differ in the choice of virtual sources used to represent the sound field and the methods used to estimate the source parameters.

Spatial Fourier Transform, Least Squares, and Spherical Waves

The first method was based on a sound field representation by plane waves, which are the general solutions of the wave equation in Cartesian coordinates. The calculation of source strengths in the earliest holography methods used a discrete spatial Fourier transform of data measured by a rectangular array with equally spaced microphones. This method was later extended to cylindrical and spherical coordinates (Williams 1999).

Since a Fourier transform is mathematically equivalent to minimizing the squared error between the predicted and measured sound pressures at the measurement locations, the source strengths in the Fourier-based holography methods can be calculated by a direct use of least squares optimization.

The least squares approach has been widely used in another category of holography methods, the equivalent source method (Ochmann 1995), which is now the most commonly used holography technique.

> *The beamforming method can remove interference caused by known sources.*

The first equivalent source method was developed based on a representation using a distribution of monopoles (i.e., point sources) on an imaginary surface located just behind the actual source surface. The monopole distribution representation is based on the theory of single-layer potential representations of the wave equation. That representation can be extended to include dipole distribution representations (i.e., a double-layer potential) as well as methods employing a combination of monopole and dipole distributions. The latter approach, referred to as *inverse boundary element holography*, is derived from the boundary integral form of the wave equation.

It is also possible to use spherical waves to construct orthogonal velocity distributions on the actual source surface and use these distributions as equivalent sources in holography.

In addition to these various field representations derived from the mathematical properties of the governing equation, there are equivalent source methods involving representation bases with stronger physical meanings, such as multipole series, structural vibration modes, and acoustic radiation modes. Holography methods that employ bases with clearer physical meanings usually yield better modeling efficiency since the actual source generation mechanism is closely represented by the assumed basis functions.

Most source localization methods have been developed in anechoic environments, which are not likely to be the case in practice.

Limitations

Some source information either cannot be detected by measurements or is very sensitive to measurement noise (Nelson and Yoon 2000). Problems in estimating source information from measurements in acoustical holography may result from one or more of the following three possibilities:

- The number of sources that needs to be included in the model is larger than the number of microphones available (e.g., a model with monopoles distributed over a large source surface).
- The resulting sound field decays very quickly when propagating away from the source, so that when the sound pressure due to these source components arrives at the array, it is close to or even smaller than the measurement noise.
- There are too many closely located (i.e., oversampled) measurements (several measurement locations capture the same information), leading mathematically to an ill-conditioned problem in source estimation.

Challenges of Existing Methods

In every step of each of the many types of acoustic localization or visualization techniques, there are many choices of parameters and calculation procedures. A different choice or a modification in any of them can result in differences in the localization and visualization performance, and the performance differences among various methods can be quite large.

Lack of Guidelines

One significant challenge in practical applications is that, at present, nothing is clearly better than "try it and see" when judging which methods are most suitable for a specific engineering application. Researchers and engineers choose method types and select and modify various model components according to their experience and their understanding of the source mechanism.

Although there are some general guidelines such as choosing a source basis similar to the actual source both in terms of physical mechanism and geometrical dimensions, they are far from systematic. Also, most source localization methods have been developed for sources in anechoic (i.e., echo-free) environments, which are not likely to be the case in practice. Thus, another application difficulty is the removal of the influence of reflections and scattering from the actual measurement environment.

Stationarity vs. Moving or Transient Sources

Most acoustic localization methods assume stationarity, meaning that the sound field characteristics do not change over time, a requirement that follows from their frequency domain formulation. This assumption prevents localization techniques from being implemented for either transient sources (e.g., explosions) or moving sources.

Some holographic procedures are based on time-domain convolution. But time-domain source localization is an area that requires further research to find routine application in practice.

When considering the localization of moving sources (e.g., high-speed trains), visualization when the motion is known is much easier than when it is unknown. When the source trajectory is given, there are several options: remove the Doppler effect on the stationary array measurements, incorporate the sound field expression of moving sources in the holography or beamforming models, or virtually construct measurement signals that would be obtained if the array had the same motion as the source. However, localization of sources with unknown motions without additional motion capture tools is still an open issue where few practical solutions are available.

Hardware: Cost, Interference

To ensure good localization performance, most methods require many microphones—perhaps hundreds—and the cost of this measurement hardware limits the application of these techniques.

In addition, the presence of the microphone array and the related mounting systems and wiring can lead to nonnegligible acoustic scattering that contaminates the microphone measurements and thus impairs the source localization performance. Any object, even a relatively small microphone placed in a sound field, perturbs the sound field that is to be measured, adversely affecting the accuracy of the source visualization. That problem is made worse by the presence of both the support structure that holds the microphones in position and the cabling that connects dozens or hundreds of microphones to the data acquisition system. So there is an incentive to make sound pressure measurement methods as noninvasive as possible.

At present, MEMS (microelectromechanical systems) microphones are being widely adopted to minimize scattering effects. These microphones-on-a-chip can be very small compared to conventional condenser-type microphones. Further, their power requirements are very modest. It may be that the vibration induced by the sound pressure itself could power the microphones, eliminating the need for external power supplies. Transmission of the signal to the data acquisition system could conceivably be done wirelessly, completely eliminating the need for cables.

These steps would represent a very positive improvement. But in the end, it would be desirable to eliminate the microphones entirely in favor of a completely noninvasive measurement procedure.

Future Applications and Potential Connection with Other Techniques

Fault Diagnostics

One application of acoustic localization or visualization techniques that is likely to attract wide attention in both industry and academia is implementation in online condition monitoring and fault diagnostics of mechanical systems, such as wind turbines and various mechanical subsystems in vehicles.

A reliable online diagnostics system requires "clean" data to be obtained from each potentially faulty component without interrupting the machine operation. But it is often difficult or impossible to apply sensors directly to components in every product. It is preferable to use acoustical data measured at microphones a certain distance from the targeted mechanical component and then use source localization techniques as a virtual sensing tool to measure vibroacoustic information from each component. Acoustic measurements are usually more cost effective than alternatives such as optical measurements.

The primary stimulus of the study of sound source localization in fault diagnostics is the emergence of machine learning (ML) research and applications. There could be many valuable outcomes from investigating which ML algorithms are more applicable in fault diagnostics, what signal characteristics are more suitable for training ML models, and how to develop source localization techniques to better obtain those signal characteristics. The development of autonomous vehicles, for example, raises the demand for improved fault diagnostic tools for a variety of mechanical systems to ensure safety and driving comfort.

Autonomous vehicles raise the demand for improved fault diagnostic tools for mechanical systems to ensure safety and driving comfort.

Virtual Noise Control Design and Active Noise Control

An attractive aspect of the holographic procedure is its application in virtual noise control design. Since the holographic procedure involves the creation of a source plane, it supports, for example, the creation of a virtual stethoscope: it is possible to synthesize, and thus listen to, sound generated at any point on the source surface. The synthesized signals can be analyzed, using sound quality software, to identify regions from which objectionable sounds are radiating.

Further, the sound radiation from particular parts of a complex source can be virtually "turned off" to gauge the noise control impact from either reducing the sound generated by a particular component or applying a shield. In this way, it would be possible to both quantify the potential reduction in radiated sound power and assess the impact of changes on the perceived sound quality. Engineers would be able to accurately assess the relative benefit of different noise control solutions, thus potentially eliminating expensive prototyping stages and significantly speeding up the design and development process.

Source visualization techniques can also provide benefits to active noise control: i.e., the use of secondary noise sources to generate sound fields that cancel unwanted sounds. Currently, the increasing on-chip computing power and reductions in electronic hardware cost make it desirable to perform multichannel active control over a relatively large spatial region. However, an active control algorithm can sense the noise control performance as measured by error microphones only at specific locations in the target region; good noise control performance at those microphone locations does not guarantee good performance at other locations in the region.

If techniques such as acoustical holography can be combined with active noise control systems, it will be possible to provide virtual measurements of the sound field throughout the target region, and these measurements can be used in the active control algorithm. In principle, the performance of such an active noise control system will give much better global performance than traditional methods.

Looking Ahead

In recent years, it has been shown that the small fluctuations in air density that result from the passage of sound waves can be detected with laser systems (Sonoda and Nakamiya 2014). This observation offers a very promising path forward. At present, this procedure cannot be used to make a precisely localized measurement, but perhaps through the use of multiple laser beams interacting at a point, the density and sound pressure fluctuation could be detected at an array of points, whether sequentially, by scanning, or simultaneously with a sufficient number of laser channels. And further in the future, it may be possible to measure sound pressure over an entire planar surface at once by using pulsed laser sheets (by analogy to double-pulse particle-image velocimetry).

Although these suggestions may seem like science fiction, we are sure that ultimately it will be possible to make noninvasive sound pressure measurements over large surfaces, thus providing very finely resolved data as input to holographic and beamforming procedures.

References

Chiariotti P, Martarelli M, Castellini P. 2019. Acoustic beamforming for noise source localization: Reviews, methodology and applications. Mechanical Systems and Signal Processing 120:422–48.

Dolph CL. 1946. A current distribution for broadside arrays which optimizes the relationship between beam width and side-lobe level. Proceedings of the IRE 34(6):335–48.

Geyer T, Sarradj E, Giesler J. 2012. Application of a beamforming technique to the measurement of airfoil leading edge noise. Advances in Acoustics and Vibration 2012:905461.

Johnson DH, Dudgeon DE. 1992. Array Signal Processing: Concepts and Techniques. New York: Simon & Schuster.

Nelson PA, Yoon SH. 2000. Estimation of acoustic source strength by inverse methods, part I: Conditioning of the inverse problem. Journal of Sound and Vibration 233(4):639–64.

Ochmann M. 1995. The source simulation technique for acoustic radiation problems. Acta Acustica united with Acustica 81(6):512–27.

Sonoda Y, Nakamiya T. 2014. Direct detection of sound wave by light. IEEE 3rd Global Conf on Consumer Electronics, Oct 7–10, Tokyo.

Williams EG. 1999. Fourier Acoustics: Sound Radiation and Nearfield Acoustical Holography. London: Academic Press.

Numerous resources are available to provide guidance for engineers and others in addressing noise concerns.

Resources for Noise Control Engineering

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George C. Maling Jr.

Human-made noise is ubiquitous in daily life, from the background hum of the computer or refrigerator to the drone of leafblowers, the passing roar of an overhead airplane, or the beeping of a backing truck. Distinct from background or transient noise, sustained exposure to high levels of noise constitutes a health hazard. In addition to causing loss of hearing, it can raise stress levels and contribute to high blood pressure (Rathner 2014). For these reasons experts, techniques, and resources are available to reduce noise levels and mitigate their impacts.

In the workplace, the National Institute for Occupational Safety and Health (NIOSH; part of the Centers for Disease Control and Prevention, CDC) has determined that noise levels above 85 dBA[1] pose a health hazard and that the hazard increases with exposure time (NIOSH 1998). The institute estimates that 22 million workers are exposed to hazardous noise.[2]

Ideally, an individual skilled in noise control engineering should be involved during the design stage of a product or machine. But the reality is that problems with noise must often be solved in the field and sometimes

[1] Most noise levels are A-weighted; that is, the sounds are frequency weighted according to the A-weighting curve, which approximates human hearing for midlevel sounds. Note that it is the level and not the decibel that is A-weighted. Nevertheless, A-frequency-weighted levels are often expressed as dBA or dB(A).

[2] https://www.cdc.gov/niosh/topics/noise/about.html

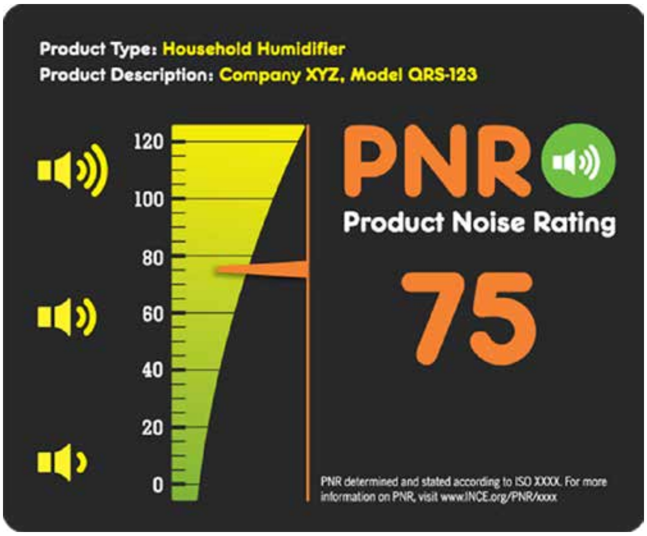


FIGURE 1 Sample of a product noise rating (PNR) label. Used with permission from Matt Nobile.

by staff engineers who do not necessarily have training or experience in noise control engineering. This article identifies the many resources available to individuals and organizations that need to address noise problems.

Buy Quiet

"Buy quiet" programs encourage the purchase of quiet equipment. Government agencies and professional organizations have used these programs to reduce the sources and impacts of noise in workplaces as well as residences, public spaces, and national parks.

A decade ago the *Technology for a Quieter America* report (NAE 2010, p. 41) provided information on buy quiet programs and presented good reasons for noise specifications:

- They help reduce hazardous noise levels, saving the costs of a hearing conservation program.
- Speech communication in low-noise workplaces is much better than in those with high noise levels. Because no hearing protection is necessary, desired sounds such as announcements via public address systems can be clearly heard.
- Low-noise workplaces promote safety (e.g., alarms are clearly audible).
- Low-noise workplaces make it easier for workers to concentrate and reduce fatigue.
- Low-noise workplaces are more productive and more comfortable.

Key Elements of a Buy Quiet Program

The five key elements of a buy quiet program are

- selection of a metric to describe the noise emission,
- selection of a measurement method,
- specification of equipment operating conditions,
- declaration of the noise emission value, and
- verification.

Noise emission metrics: The metric widely used to describe noise emissions is the A-weighted sound power level of the product, and there are many national and international standards with detailed procedures on how to determine this quantity. A simplified version of this metric, the product noise rating (PNR), has been developed (Nobile 2011a,b). Figure 1 shows a modern version of the full label, with not only the PNR value for the particular product but also the overall PNR scale so that the purchaser can see at a glance how loud (or quiet) the product is. This version is being considered for roll-out by the Institute of Noise Control Engineering of the USA (INCE-USA).

The PNR is numerically equivalent to the A-weighted sound power level but does not involve technical units. Such a rating might be more acceptable to buyers and producers of noise-emitting equipment. When published in product literature or on a website, the PNR would be displayed as a uniform, recognizable label. A condensed version of the PNR label or "logo" may be used when space is limited or for other applications.

Measurement methods: Measurement methods are well established in US and international standards, as discussed by Robert Hellweg (2021) in this issue.

Operating conditions: The operating conditions for the measurements must be specified.

Declaration and verification of the noise emission value: International standards specify how a noise emission value should be declared, taking into account measurement variation in a production series and between laboratories. The publication of a new American National Standard on noise declaration and verification (ANSI 2020) strengthens the case for buy quiet programs in the United States.

Overview of Buy Quiet Programs

In the late 1990s and early 2000s, NASA began a buy quiet program largely through the efforts of Beth

Cooper.[3] The program is available today as an online Buy Quiet Roadmap[4] that can guide efforts for industry; for example, a roadmap for construction firms has been developed (Nelson 2011).[5]

NIOSH strongly encourages industry sectors to establish their own buy quiet program and identifies components of such a program, including the following:

- management support of a buy quiet policy, including a commitment to low-noise purchases, application of cost-benefit analysis in purchasing decisions, and, at the highest level, the purchase of quiet equipment regardless of cost; and
- an inventory of the noise emissions of existing equipment.

With respect to costs, not only the purchase price but also lifecycle costs should be considered, such as health costs, lost productivity, and the costs of a hearing conservation program. According to NIOSH, "conservative estimates provide $100 per dBA of savings when purchasing a quieter product; this savings is applicable across a variety of machinery and equipment."[6]

A database of noise emission values is also part of a buy quiet program. NIOSH developed a database of noise from power tools; other databases are also available:

- IBM maintains information on the sound power level of its products to enable customers to determine noise levels in data processing centers.[7]
- The European Union has noise requirements on construction equipment (European Parliament 2000) and maintains an extensive database of products and their declared noise emission values.
- New York City has created a database of noise levels for construction equipment to provide guidance to contractors for using quiet equipment in city construction projects.
- The Laborers Health and Safety Fund of North America also has information on products used in construction, with guidance on the selection of quiet saw blades and diesel generators.

The International Institute of Noise Control Engineering (I-INCE) develops reports on various noise topics. A recent report "outlines guidelines for 'Buy Quiet' programs to limit occupational noise and to assist professional buyers of industrial equipment" (Beltman et al. 2018, p. 5):

- research by a buyer and seller on low-noise technology
- establishment of a database of product noise emissions
- selection of a noise emission standard and specification
- determination of operating conditions
- measurement and verification.

The report also reviews the history of such programs and includes a long list of references.

Online buy quiet roadmaps are available for construction and other industries.

Stakeholders in the Solution of Noise Problems

A number of professional and government organizations are available to assist industries with the control of noise sources.[8]

Professional Organizations

Institute of Noise Control Engineering of the USA

INCE-USA is dedicated to the solution of environmental, product, machinery, industrial, and other noise problems. It certifies members and other practitioners in noise control through a program of written material and an examination. It also publishes the peer-reviewed *Noise Control Engineering Journal* and, jointly with I-INCE, the magazine *Noise/News International.*

[3] Ms Cooper is an acoustical engineer who consults for NASA on hearing conservation, noise control engineering, and acoustics.

[4] https://buyquietroadmap.com/buy-quiet-purchasing/buy-quiet-process-roadmap/

[5] In addition, an International INCE symposium in 2011 explored myriad dimensions of noise reduction (https://www.bruit.fr/buyquiet/buyquiet2011/index.htm).

[6] https://www.cdc.gov/niosh/topics/buyquiet/default.html

[7] IBM Knowledge Center, Power8: Acoustics, www.ibm.com/support/knowledgecenter/POWER8/p8ebe/p8ebe_acoustics.htm?mhsrc=ibmsearch_a&mhq=acoustic%20noise%20declaration

[8] Military organizations, those that deal with transportation noise, and other entities with less extensive programs are not included here.

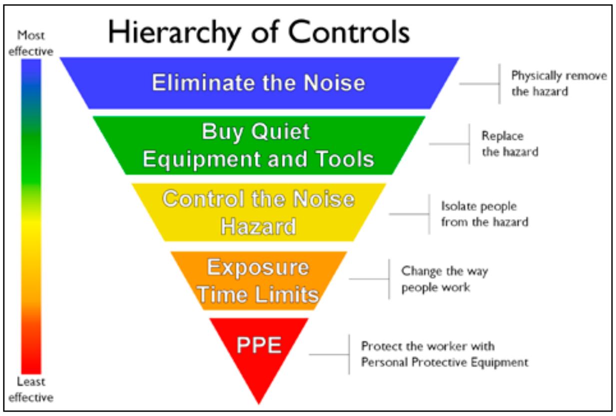


FIGURE 2 Hierarchy of actions for control of industrial noise.

INCE-USA sponsors national conferences on noise control engineering (NOISE-CON) when international (INTER-NOISE) congresses are held overseas. It also offers short courses on noise control at annual meetings as well as a distance learning program, maintains a digital library of noise publications (over 20,000 articles), and gives awards to both professionals and students. Many members offer consulting services in noise control engineering and architectural acoustics.

International Institute of Noise Control Engineering

I-INCE is a consortium of institutes of noise control engineering and acoustical societies around the world. It sponsors an annual INTER-NOISE congress and produces technical reports on various subjects related to noise control engineering (e.g., Beltman et al. 2018).

National Council of Acoustical Consultants

NCAC members offer consulting services for architectural acoustics, mechanical systems noise and vibration control, industrial workplace noise, environmental noise evaluation and control, product and system design, and forensic acoustics. The website has a reference tool to help visitors find a consultant matched to their need.

Other Professional Organizations

A number of associations in the United States address the broad field of acoustics and engineering and have noise control as part of their activities. They include the following:

- Acoustical Society of America (ASA)
- American Institute of Aeronautics and Astronautics (AIAA)
- SAE International (formerly the Society of Automotive Engineers)
- ASTM International (formerly the American Society for Testing and Materials)
- American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE)
- American Industrial Hygiene Association (AIHA)
- American Conference of Government Industrial Hygienists (ACGIH)
- National Hearing Conservation Association (NHCA)

Government Organizations

National Institute for Occupational Safety and Health

NIOSH conducts research on various aspects of workplace safety, including noise, and informs the public of the consequences of exposure to hazardous noise levels.

NIOSH's recommended level for exposure to occupational noise is lower than that of the Occupational Safety and Health Administration (OSHA). The scientific basis for its recommendation of 85 decibels is the time-weighted average exposure for an 8-hour day (NIOSH 1998). The 1998 update of a 1972 document expands its guidance to include, among other things, the establishment of a hearing loss prevention program.

An earlier document (NIOSH 1978) may be useful when long-standing problems exist. Among other items, it provides advice on the analysis of noise problems and a long list of case histories for industrial noise control.

NIOSH advocates application of the hierarchy of controls, an inverted pyramid of actions to reduce noise exposures (figure 2). The pyramid gives preeminence to the elimination of hazardous sources of noise. If the source cannot be eliminated, then perhaps there is a substitute process that is less noisy. If elimination and substitution are not viable solutions, then engineering noise control solutions should be developed that will isolate the worker(s) from the noisy operation. Administrative controls can be used to limit the exposure times of workers to noisy operations. Finally, hearing protection devices are at the bottom of the pyramid. Together with administrative controls, they are considered less effective because they depend on individual worker compliance with the time limits for exposure and wearing hearing protection properly—if at all. Hence, noise control engineering is recommended as the primary method to control noise.

The NIOSH Safe-in-Sound Excellence in Hearing Loss Prevention and Innovation Award recognizes individuals and organizations that have proactively reduced hearing loss in occupational settings. The award program is administered in cooperation with the Council for Accreditation in Occupational Hearing Conservation and the National Hearing Conservation Association. The annual awards, for excellence and for innovation, have been presented to large industrial corporations, government agencies, military and law enforcement, and academic researchers.

In 2020 the award was given to an international consortium involved in efforts to control noise and protect hearing on the International Space Station, where astronauts are exposed to noise 24 hours a day, 7 days a week. The international group's work to control noise and protect the astronauts' hearing is accomplished in part through the purchase of quiet equipment and regular monitoring of noise in the station.

Occupational Safety and Health Administration

OSHA is the primary US regulatory body for limits on occupational noise exposure. It has produced a wealth of information on control of noise in industrial situations and has a strong interest in seeing noise levels reduced, even when they are below regulatory limits because such noise can affect communications between workers and contribute to stress, anxiety, high blood pressure, and fatigue. A particularly useful OSHA publication is the *Technical Manual* (OSHA 2013), in which chapter 5 details different kinds of noise, industries, regulations, noise controls, measurements, and references and resources.

OSHA has also announced the 2021 Safe+Sound program[9] for all aspects of workplace safety including noise, and offers consulting services for workplace issues independent of its regulatory program.

It is well established that exposure to hazardous noise produces hearing loss that is not reversible. Behind hypertension and arthritis, hearing loss is the most common chronic condition for adults. OSHA sets a permissible noise limit and also requires that an organization have a hearing conservation program when time-weighted average levels or average 8-hour levels exceed 85 dBA.

The OSHA permissible exposure limit for noise is 90 dBA with a 5 dB exchange rate. That means there is a trade-off between permissible level and time; for example, the limit would be 95 dBA for a 4-hour exposure, or 100 dBA for a 2-hour exposure. The OSHA manual allows a 10 dB increase if hearing-protective devices are used. But, as noted above, use of such devices is generally regarded as the last in a series of measures that should be used to control noise and reduce its impacts.

The OSHA limits are widely regarded as too permissive. For example, with regard to exposure to 85 dBA for 8 hours with an exchange rate of 3 dBA, OSHA's sister organization, the Mine Safety and Health Administration (MSHA), has stated that scientific evidence in favor of these levels is strong.[10] Although the 85/3 dB criterion is generally accepted as a better limit for prevention of hearing loss, MSHA has not implemented a lower level mainly because of concerns about costs to small mining organizations.

Exposure to hazardous noise produces hearing loss that is not reversible.

There is strong industry opposition to a reduction in the noise level permitted by OSHA, as illustrated by one attempt to change the noise exposure regulation. In 2011 OSHA issued a notice of proposed rule making that would change the definition of the word *feasible* as used in the noise regulations. Generally, the word has covered constraints such as schedules, costs, and ability to make changes. The new definition, based on a US Supreme Court definition in a case unrelated to noise emissions, defined *feasible* as "capable of being done." The only constraint on the new definition as proposed for noise would be that the changes would not bankrupt a company required to lower noise levels. After considerable industry pressure on OSHA through the Small Business Administration and Congress, the proposal was withdrawn.

Environmental Protection Agency

The congressional Noise Control Act of 1972 directed the EPA's Office of Noise Abatement and Control (ONAC) to regulate noise, including the purchase of low-noise-emission products,[11] and to issue informa-

[9] www.osha.gov/safeandsound

[10] Federal Register 61(243):66367 (1996).

[11] Code of Federal Regulations 40 CFR §203: Low-Noise-Emission Products, https://www.govinfo.gov/app/details/CFR-2011-title40-vol25/CFR-2011-title40-vol25-part203

tion on product noise labeling.[12] The program never progressed enough to identify products that should be labeled (with the exception of portable air compressors, motorcycles, and hearing-protective devices). The procedures are still part of the Code of Federal Regulations, but in 1981 the office was defunded by the Reagan administration and that effectively ended EPA interest in buy quiet and low-noise products.

It may seem irrelevant to discuss events from almost 50 years ago, but the program resulted in the so-called "levels document" (EPA 1974), which defined noise levels to protect public health and welfare with an adequate margin of safety. Another output was demonstration projects that determined what could be done in the way of noise control (e.g., the low-noise design of trucks).

Some EPA noise regulations are a burden on manufacturers to meet out-of-date standards that do not account for modern noise control technology.

Some EPA noise regulations remain in place and are a burden on manufacturers to meet out-of-date standards that do not account for modern noise control technology. Such regulations affect motorcycles and air compressors, for example.

Other Government Agencies

Many federal and state agencies have noise programs. Federal agencies include the following (again, nonmilitary, nontransportation):

- Department of the Interior (National Park Service)
- Department of Energy
- NIH National Institute on Deafness and Other Communication Disorders
- CDC National Center for Environmental Health
- CDC National Center on Birth Defects and Developmental Disabilities

Educational Institutions

Universities offer many resources for noise control engineering. Adnan Akay (2021) details what students should learn in such programs and cites specific subjects and areas of study.

In 2019 two workshops were held on the subject of noise control engineering education. The work of the participating organizations and universities is outlined in this issue (Wood and Maling 2021).

In addition, many entities such as universities, professional organizations, and consulting firms offer short courses on noise control, most frequently in conjunction with a conference.

Conclusion

There are numerous resources for noise control. This information should be especially useful for industry, where budgets cannot support one or more noise control engineers together with the facilities required for noise reduction. Companies may designate an engineer on staff to be responsible for noise control; with, perhaps, little or no training in noise control, that individual must look for resources. It is hoped that the information in this article will provide some guidance to assist individuals in becoming educated in the field.

References

Akay A. 2021. Noise control engineering and education. The Bridge 51(2):13–18.

ANSI [American National Standards Institute]. 2020. ANSI/ASA S12.61, American National Standard Declaration and Verification of Noise Emission Values of Machinery, Equipment, and Products. New York.

Beltman M, Hellweg R, Kurtz P, Tourret J, Jacques J. 2018. I-INCE TSG 10 Buy Quiet Report, rev. 0.98. Zürich: International Institute of Noise Control Engineering.

EPA [Environmental Protection Agency]. 1974. Information on levels of environmental noise requisite to protect public health and welfare with an adequate margin of safety. Prepared by the Office of Noise Abatement and Control. Washington.

European Parliament. 2000. Directive 2000/14/EC of the European Parliament and of the Council, 8 May. Official Journal of the European Communities L 162. Strasbourg.

[12] 40 CFR §211: Product Noise Labeling, https://www.govinfo.gov/app/details/CFR-2002-title40-vol21/CFR-2002-title40-vol21-part211

Hellweg RD Jr. 2021. Voluntary national and international noise standards for products and machines. The Bridge 51(2):27–33.

NAE [National Academy of Engineering]. 2010. Technology for a Quieter America. Washington: National Academies Press.

Nelson D. 2011. Adaptation of NASA buy-quiet process roadmap for construction firms (NIOSH Publication 212-2011-M-38379). Washington: National Institute for Occupational Safety and Health.

NIOSH [National Institute for Occupational Safety and Health]. 1978. Industrial Noise Control Manual (Report 79-117). Cincinnati.

NIOSH. 1998. Criteria for a Recommended Standard: Occupational Noise Exposure, Revised Criteria (Publication 98-126). Cincinnati.

Nobile MA. 2011a. A simplified noise rating method for the general public. Proceedings, INTER-NOISE 2011, Sep 4–7, Osaka.

Nobile MA. 2011b. PNR: A simplified product noise rating for the general public. Presentation, NIOSH Buy Quiet Workshop, Nov 9–10. Online at https://www.cdc.gov/niosh/docket/archive/pdfs/niosh-247/0247-110911-nobile_pres.pdf.

OSHA [Occupational Safety and Health Administration]. 2013. Technical Manual, Section III, Chapter 5: Noise. Washington.

Rathner JL. 2014. Noise: Harmful to hearing, harmful to blood pressure. Washington: Laborers' Health & Safety Fund of North America.

Wood EW, Maling GC Jr. 2021. A decade and a half of progress toward reducing noise in the United States. The Bridge 51(2):7–12.

Advantages of nuclear batteries include low-enriched fuel, simple design, mass manufacturing, minimal site preparation, and semiautonomous fleet operation.

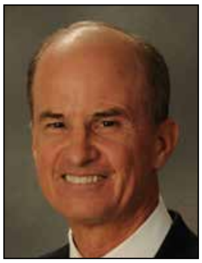
A Strategy to Unlock the Potential of Nuclear Energy for a New and Resilient Global Energy-Industrial Paradigm

Jacopo Buongiorno, Robert Freda, Steven Aumeier, and Kevin Chilton

Jacopo Buongiorno

Robert Freda

Steven Aumeier



Kevin Chilton

"Experts would be mobilized to apply atomic energy to the needs of agriculture, medicine, and other peaceful activities. A special purpose would be to provide abundant electrical energy in the power-starved areas of the world.… Thus the contributing Powers would be dedicating some of their strength to serve the needs rather than the fears of mankind." – Dwight D. Eisenhower, Atoms for Peace speech, United Nations, December 8, 1953

The United States' energy production and delivery architecture, developed throughout the 20th century, provided the foundation for dramatic

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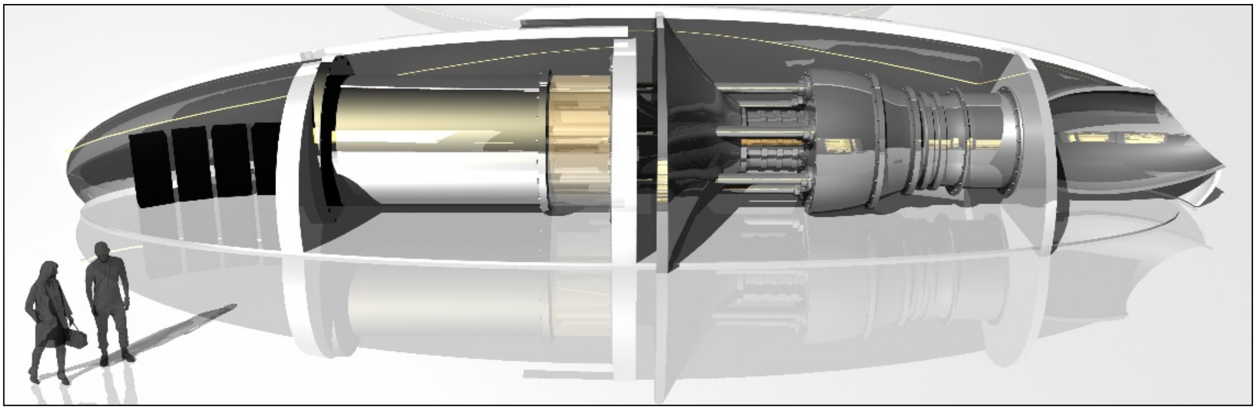

FIGURE 1 Cutaway rendering of the MIT nuclear battery concept showing important components such as the instrumentation and control module, the reactor, and the power module.

economic and standard of living advances. But the centralized architecture lacks the resilience to withstand known, predictable, and unpredictable 21st century external threats, whether man-made or natural.

In the interest of market growth, the architecture has become significantly more complex and vulnerable since 1995, producing risks, threats, and unintended consequences across multiple systems: information, energy, basic resources, and the atmosphere. The current design of energy production and distribution systems will continue to increase stress in developed nations and will not meet the needs of developing nations. In addition, adaptation to a warming climate is already a clear and present need.[1] Strategically, it is imperative to prepare for worse yet to come, sooner rather than later. Thus a new type of distributed energy resource is needed that is low-carbon, compact, stable, flexible, and geographically unconstrained.

The United States must derisk its infrastructure and adapt to climate change simultaneously. Strategies and policies formulated before the turn of the century are insufficient to this need. New rapid development paths are needed to enable flexible energy-industrial systems that produce energy that is both dense enough and cheap enough to compete with fossil fuels and adaptable enough to deal with change. Greater resilience to new and already evident levels of risk must go hand in hand with increased efficiency in the generation and delivery of electric power, heat, goods, and services for all sectors of the economy, from industry to businesses, transportation, buildings, and agriculture.

[1] NOAA estimates that the cost of US weather and climate disasters has been accelerating dramatically, from a total of $400 billion over 19 years (1980–99) to $600 billion in 2016–20 (Smith 2021).

What resource can address these challenges and power the world's ever growing needs for adaptation and resilience? The solution presented in this paper is distributed portable nuclear energy colocated with end users. This solution bypasses the need for massive, low-use centralized infrastructure such as the national grid, energy storage, and fuel distribution networks. And it likely has the flexibility to deal with further unknowns, which have become endemic over the last 20 years and are a certainty over the next 20.

Nuclear Batteries: A New Way in Energy

Advances in embedded intelligence and adaptive manufacturing and materials are enabling the development of new small, flexible, plug-and-play nuclear energy systems that we call *nuclear batteries*.[2] The nuclear battery (NB), also called a *microreactor*, is a small but powerful stand-alone energy platform (figure 1) that can be integrated into industrial, manufacturing, and other functions. NB systems—the industrial equivalent of a AAA battery—can operate for up to 10 years, after which they are "recharged" with new nuclear fuel. Among their numerous advantages,

- NBs can power almost anything with no need for continuous fuel supply.

[2] Interestingly, the Idaho National Laboratory uses a similar term, *fission battery*, for a microreactor with the following five features: cost competitive, fabricated, installed, unattended, and reliable (Federal Laboratory Consortium workshop series on technology innovations for fission batteries).

- They can provide any desired amount of electricity and heat on site, eliminating the need for long-distance transmission and large centralized infrastructure.
- A single 10 MW NB can power some 7000–8000 homes, a large shopping mall, or a midsize data center, or produce enough desalinated fresh water for over 150,000 people.
- They use a fully standardized, mass-produced, factory-fueled, simple design with few moving parts.
- They combine a small nuclear reactor and a turbine to supply significant amounts of heat and/or power (on the order of 15–30 MWt or 5–10 MWe) from a very small footprint.
- They are compact enough to fit in standard shipping containers for transport to the site of interest, where a unit can be installed and made operational in a matter of days or weeks.
- Embedded intelligence and established advanced monitoring paradigms enable semiautonomous and remotely monitored operation, inherent digital security, and the potential for highly efficient global fleet operational models.
- They use low-enriched uranium fuel.
- "Exhausted" and properly cooled NBs can be safely shipped back to a centralized facility for refueling and refurbishment.
- There is no need for high-level radioactive waste handling or storage at the user site.[3]
- NBs may provide an alternative and a complement to overbuilt variable energy approaches, coupled with energy storage.

The combination of low-enriched fuel, simple design, mass manufacturing, minimal site preparation, and semiautonomous operation can yield an economically competitive system in short order, for installation in various scenarios (figure 2).

Importantly, NBs are designed with features that achieve the three fundamental nuclear safety functions without operator intervention: (1) rapid shutdown of the fission chain reaction in the event of an anomalous condition, (2) adequate cooling of the nuclear fuel during shutdown, and (3) no uncontrolled release of materials into the biosphere (Reyes et al. 2020). These features significantly reduce the possibility of accidents like those at Three Mile Island, Chernobyl, and Fukushima.

Physical security for NBs during operation will be achieved with a combination of design features (e.g., a robust fuel and containment shell), layout (e.g., below-grade embedment), and remote monitoring and defense.

Because cybersecurity is a potential concern for any autonomous system, the NB's inherent safety features are such that even a knowledgeable operator would not be able to damage the nuclear fuel or cause a radioactivity release. Most NB designs under consideration make it physically impossible to cause a runaway reaction (e.g., by manipulating control mechanisms) or use instrumentation and controls to interrupt residual heat removal from the core. Cyberdefense layers are thus aimed primarily at ensuring continuity of service.

A More Resilient Energy-Industrial Infrastructure

Complexities and Risks of Current Systems

Today's electrical grid is the product of a century-long coevolution of markets, fossil fuels, and centralized power production. Combined with urbanization, the result is a highly specialized symbiotic interconnected system, requiring tight controls over electricity production fuels (coal, oil, natural gas, uranium) and their transport (pipeline, truck, rail) to large centralized power plants, lengthy power lines for distribution, and supply and voltage synchronization (provided by precise timing from GPS satellites) to deliver energy to demand.

The recent addition of variable renewables has introduced further complications. While renewables play a role in decarbonizing the grid, they contribute to vulnerabilities in systems that are already fragile and susceptible to external perturbations, whether natural (e.g., tropical storms, tornadoes, earthquakes) or man-made (e.g., malicious cyber-, antisatellite, or kinetic attacks). The prolonged blackouts in California and

[3] A national waste repository is still required, but NB shipment would be a routine activity akin to today's transportation of used nuclear fuel. Since 1971 there have been at least 25,000 cargoes of used fuel transported, covering many millions of kilometers on both land and sea, including sea voyages transporting more than 4000 casks, each about 100 tons. In the United States there have been over 3000 shipments of commercially generated spent nuclear fuel without any radiological releases to the environment or harm to the public. Most shipments are between power plants owned by the same electric utility, to share storage space for used fuel (WNA 2017).

Texas in 2020 and 2021 are a prelude of what's to come.

Large-scale electrical energy storage, proposed as a means to manage the variable generation, would increase costs, complexity, security concerns, and failure modes.

Advantages of NB Energy Architecture

NBs afford a fundamentally different energy architecture:

- They can safely deliver clean electricity and heat to nano- and microenergy grids and supply networks on-site anywhere on the planet and at various scales, without being connected to a national grid or fuel pipeline.
- As standalone supply and distribution systems, they are not subject to the cascading failures that affect the current centralized supply and interconnected electrical grid system.
- They can more securely and reliably provide virtually unlimited energy for local heat, food, and water production, decentralized manufacturing, synthetic fuel production, and much more.
- Unlike other distributed energy resources (e.g., rooftop solar panels, small gas turbines), NBs' combination of low-carbon and energy intensity, compactness, stability, and flexibility can enable deployment and decarbonization in every sector of the economy on a global scale.

In addition to adding energy and supply resilience to homes,

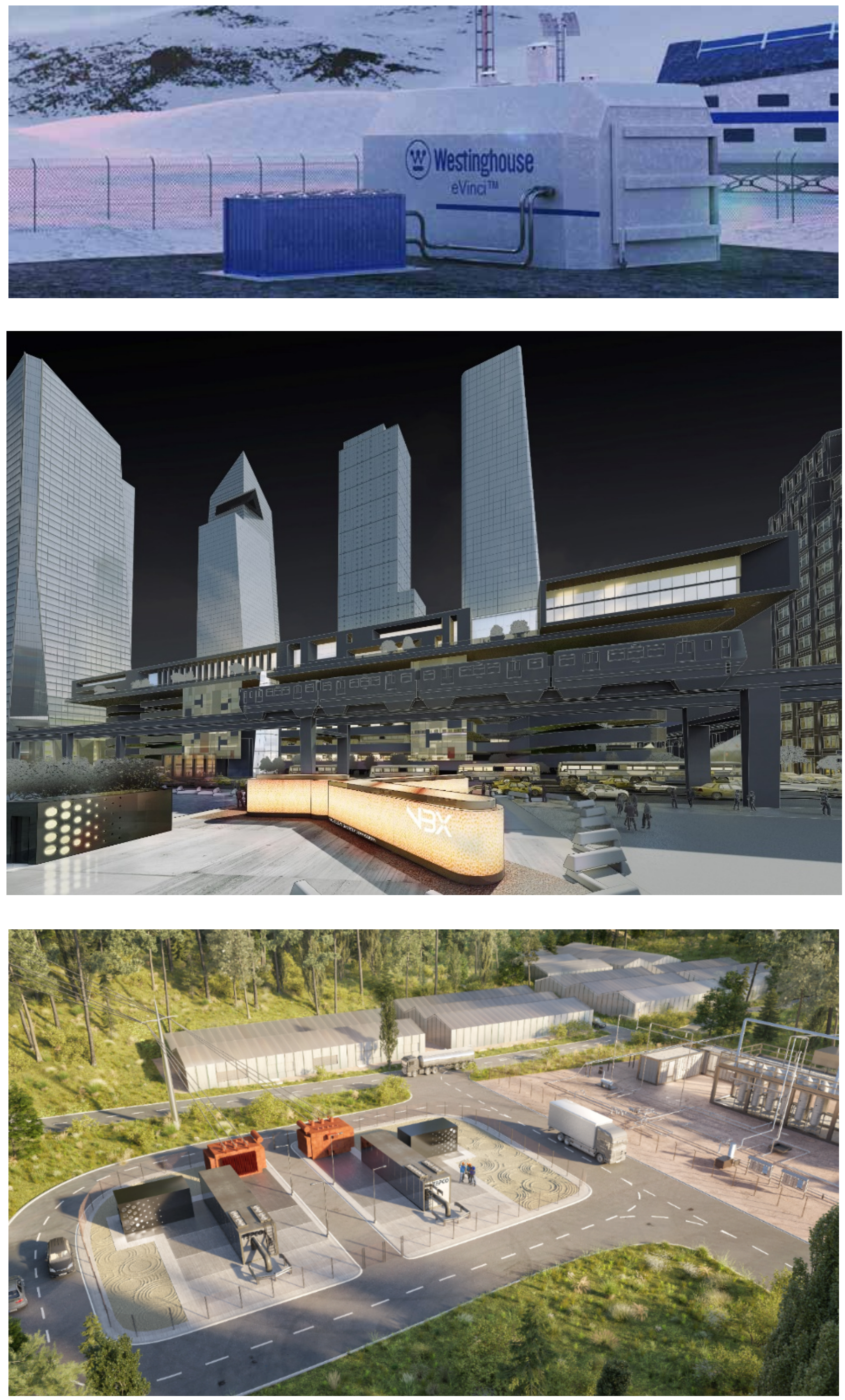

FIGURE 2 What a site with nuclear batteries (NBs) might look like. Top to bottom: the Westinghouse eVinci™ (© Westinghouse Electric Company), and notional renderings of urban (source: Instance BV) and industrial NB installations.

cities, and the industrial base, NBs can help decrease vulnerabilities of stateside and international military bases, which largely depend on the commercial grid to power their daily operations. A reliable and independent source of electricity, heat, and fuels would enable them to effectively project military power in crisis, enhancing their deterrent value vis-à-vis adversaries who might seek to neutralize them or degrade their ability to respond through attacks on the nation's power grid. Indeed, military bases would be the ideal place for the initial deployment of NB capabilities, to both enhance national security by providing a reliable and secure alternative to dependence on the vulnerable commercial grid and demonstrate to the American public the safety and effectiveness of the NB/independent grid combination.

US military bases would be ideal for initial NB deployment, to enhance national security and demonstrate to the American public NB safety and effectiveness.

To meet these and other national security needs, commercial NB systems should be developed as a flexible primary energy supply platform, pairing NB-powered nano- or microenergy grids with on-site containerized agriculture and manufacturing, district heating, data centers, air- and seaports, oceanic transport, and disaster/pandemic relief efforts, to mention just a few applications (figure 3). These sectors account for a large share of the world's grid-delivered fossil electricity, heat, and transport fuel. They will be NB market opportunities over the coming decades.

A More Efficient Economy

In addition to its lack of resilience, the 20th century energy production/delivery architecture is inefficient, in the sense of low average use of capital assets. The current electrical grid, with a load-following, supply-to-demand paradigm, uses electric generation and transmission assets at less than a 50 percent rate on average.

The grid carries the equipment to supply the maximum demand, plus large margins, to maintain service, accommodate urban growth, and (ideally) prevent localized distribution brownouts and systemwide rolling transmission blackouts. But centralized transmission systems lose 6–8 percent of the electricity generated, and energy storage loses 15–20 percent of the originally generated energy in the round trip. These losses, given the marginal economics in the first place, affect competitive profiles.

Onsite integration of energy and goods production allows for far greater use of energy and equipment for different purposes. It is the basic advantage behind systems such as "combined heat and power." Even with inexpensive storage and cheap renewable energies, centralized systems are more resource intensive, more polluting, and less economically efficient and productive than the clean direct-use on-site systems (such as KUBio or Freight Farms) that NBs enable.

We estimate that the NB designs under consideration could realize a 90 percent reduction in the amount of materials required for natural gas power and a 99 percent reduction with respect to variable renewables, on a per-unit energy-generated basis. In a high-productivity colocated supply and demand system, the apparent competitive strengths of natural gas and the grid become their weaknesses. Colocating supply (the NB) and demand (the end use) avoids the grid's losses and inefficiencies because it matches generation to demand at the local level and eliminates the need for energy transmission. For industrial production and processing, especially when a continuous energy supply is required, we estimate that colocation of NBs and users could optimize the use factor of the energy and the production equipment to 80–90 percent, using significantly fewer resources.

In a separate study (Buongiorno et al., forthcoming) we estimate that a well-designed NB could produce electricity and heat at ~70 \$/MWh and ~7 \$/MMBTU, respectively. These figures would make the NB competitive against retail electricity prices for industry and natural gas heat (with either a carbon tax or carbon capture and sequestration) almost everywhere in the world. In the direct supply production paradigm, the margins of wholesale goods produced at an NB-supplied facility could be substantially higher than those produced in factories supplied by centralized grid and industrial heating. Combined with direct-to-consumer digital channels, the NB's competitive advantages become

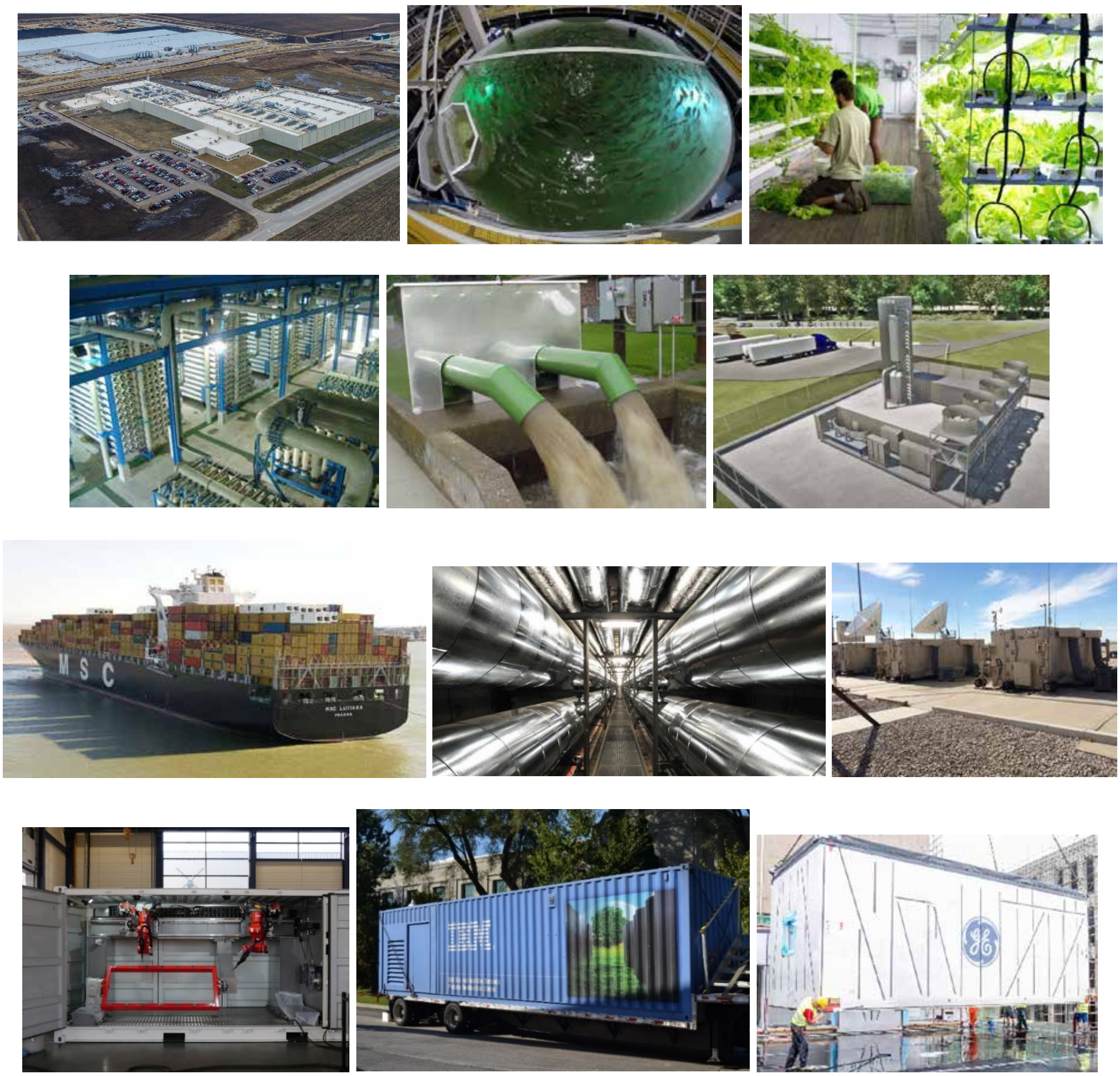

FIGURE 3 Nuclear batteries could provide electricity and heat for a myriad of colocated facilities, such as (from top to bottom, left to right): process heat for factories, indoor aquaculture (Dubai salmon farm), containerized farming, water desalination units, pumps for flood protection, charging stations for e-trucks, freight ship propulsion, district heating, military bases, 3D printing facilities (Autodesk), portable data centers (IBM), and pharma manufacturing (GE KUBio).

even stronger, while simultaneously displacing carbon-emitting fossil fuels.

NBs can increase the efficiency of energy production and delivery through close coupling of clean energy platforms with demand, using inventories of modular, small energy systems. The associated energy-industrial architecture could support affordable, scalable growth in emerging economies, and offer greater resilience in developed economies.

Global Economic Development

Communities in both the developed and developing world can benefit from smart, resilient, clean energy networks. NBs can be integrated into nano- and micro-energy grids that serve industrial and community systems, deployed in locations governed by varied local and national social and governance structures, and leverage economies of scale and simplicity. They thus can benefit from efficient means of affordable technology deployment and expansion.

Approximately 10 percent of the global population (now approaching 8 billion and growing rapidly) has no access to electricity; a large percentage rely on burning fuels that exacerbate public health crises and climate volatility.[4] In developing and energy-poor nations NBs could be deployed to isolated communities or remote areas for niche applications as well as urban, suburban, coastal, and marine nano- and microenergy grids in synergy with local energy sources. Additionally, the micro-nano energy grid approach, based on NB technology, allows incremental provisioning of capacity, enabling emerging economies to invest at an affordable pace.[5]

NB-powered sea-level protection systems (e.g., dikes and pumps) may be well suited for the most at-risk areas.

Climate Adaptation

Nations and businesses must develop plans to address climate volatility challenges. Many problems will require increased energy resources to address. Adaptation to climate volatility is likely to become a multitrillion-dollar sector, which as yet has no uniformly accepted policies or plans.[6] NB-powered mobile modular infrastructure, desalinization, and sea-level protection systems (e.g., dikes and pumps) may be well suited for the most at-risk areas.

Opportunity and Need for US Leadership

New challenges require new solutions and new ways of thinking. The United States can ill afford for indecisiveness or outmoded taboos to hinder its progress in developing this next generation of powerful, safe nuclear energy systems, and miss the opportunity to establish resilient and clean energy infrastructures based on a new systems paradigm.

NBs are substantially different from traditional energy plants, necessitating policy, market, and regulatory innovation to match technology innovation. US policy on NBs is currently dominated by programs of the Departments of Defense and Energy that envision using the batteries to power remote outposts, military bases, and mining operations, all applications in which NBs would replace extremely expensive diesel generators, which produce electricity at well over 200 $/MWh. While targeting such niche applications is a wise first step toward commercialization of the NB technology, the vision needs to be expanded.

The United States has previously made its mark with grand vision to meet challenges. Seventy-five years ago, economies and societies began to grapple with postwar rebuilding and a global surge in population. The United States led the way by steering science toward constructive and peaceful pursuits. The fields of energy, transportation, communications, and the new domain of space exploration grew at an unprecedented pace.

Under the visionary leadership of presidents Eisenhower and Kennedy, new global industries were born that would define the latter half of the 20th century. Nuclear energy, fossil fuels, and a new generation of turbomachinery powered advances and achievements in everything from aerospace to computing to pharmaceuticals and restored and raised global standards of living. The United States worked with both old and new allies to foster the technologies, institutions, standards, and market norms that would yield decades-long partnerships and pay broad dividends for millions at home and around the world.

Recent Western experience with nuclear energy is one of massive, decade-long construction projects, regulatory challenges, and costly delays. The prospects for near-term wide deployment of traditional nuclear power plants in the United States and Western Europe are grim. However, NBs present an immediate opportunity to take first mover advantage and share in the many new and emerging markets described above.

Advanced technologies from sectors beyond energy will allow for innovation in the business models used for deployment, including fleet leasing, remote monitoring and control, and semiautonomous operation. Advanced manufacturing methods can dramatically reduce the

[4] UN Sustainable Development Goal 7, https://unstats.un.org/sdgs/report/2020/goal-07/

[5] We recognize that such deployments will depend on resolution of challenges in financing, licensing, and security. That discussion is beyond the scope of this paper.

[6] As of the 25th Conference of the Parties to the UN Framework Convention on Climate Change, December 2019.

cost of NB fabrication. These attributes will need to be accommodated by modified export, regulatory, and operational norms, standards for deployment, and modernized nonproliferation policies.

Possibly most important is the need to develop broad social engagement among stakeholders, building on the 20th century Atoms for Peace approach with a 21st century paradigm of collaboration in development, demonstration, and deployment.

The United States is exceptionally well positioned to lead this endeavor for the following reasons:

- Nuclear energy enjoys broad bipartisan support in the US Congress,[7] which could yield a deliberate and cohesive policy of development, demonstration, and deployment of new nuclear technologies and systems, as well as support for export of such systems (box 1).
- The technical capabilities and collaborative action of industry, academia, national laboratories, and federal agencies have begun to lay the foundation for pioneering new nuclear systems. Nuclear energy is an opportunity for new private-public partnerships, similar to the recent evolution of the space sector, which has enabled the successful development of US commercial orbital launch services.
- Existing national lab, DOE, and NRC regulatory frameworks are adequate to permit early deployment of such systems.

Conclusion

Developing and deploying NBs and their new platform architectures, in an innovative global business and policy environment and with unprecedented stakeholder engagement, paints an exciting picture of the new state of US-sourced clean energy innovation. This is not a 15-year exercise in research. NB systems development should start now, to yield a more advanced, productive, democratized form of US-led capitalism and global responsibility for clean energy.

In the words of President John F. Kennedy, "Those who came before us made certain that this country rode the first waves of the industrial revolutions, the first waves of modern invention, and the first wave of nuclear power, and this generation does not intend to founder in the backwash.…"

[7] For example, "Sen. Manchin urges Biden to preserve US nuclear fleet," Nuclear Newswire, Apr 20, 2021.

BOX 1 Selected US federal program, policy, and regulatory support for nuclear energy

Policy

- "DFC Modernizes Nuclear Energy Policy" (US International Development Finance Corporation, Jul 23, 2020)
- DOD/DOE and microreactors
  - "Micro-Reactors Get Potential Boost in Defense Authorization Bill Provision"
  - John S. McCain National Defense Authorization Act for Fiscal Year 2019

Nongovernmental organizations

- Third Way Advanced Nuclear Campaign
- ClearPath

Enacted legislation

- Nuclear Energy Innovation and Modernization Act
- Nuclear Energy Innovation Capabilities Act of 2017
- Advanced Nuclear Production Tax Credit

Regulatory agency

- US Nuclear Regulatory Commission
  - Licenses, Certifications, and Approvals for Nuclear Power Plants
  - NRC's Transformation Journey
  - Transformation at the NRC

Federal programs

- Innovation in stakeholder engagement
  - Nuclear Innovation Workshops (INL, 2015)
  - "Energy Department Launches New Demonstration Center for Advanced Nuclear Technologies" (DOE Office of Nuclear Energy, Aug 2015)
  - Gateway for Accelerated Innovation in Nuclear (GAIN)
- Federal budgets
  - Two Thirds of a Century and $1 Trillion+ US Energy Incentives: Analysis of Federal Expenditures for Energy Development, 1950–2016 (Management Information Services, 2017)
  - Office of Nuclear Energy: Our Budget, 2019–21
- Department of Defense
  - "Pentagon awards contracts to design mobile nuclear reactor" (Defense News, Mar 9, 2020)
- Use of federal sites for nuclear technology demonstration
  - Evaluation of Sites for Advanced Reactor Demonstrations at Idaho National Laboratory (DOE OSTI, 2020)
  - "Idaho National Laboratory site permit issued for SMR project" (WNN, Feb 19, 2016)

State-level support

- "Five states have implemented programs to assist nuclear power plants" (EIA, Oct 7, 2019)

References

Buongiorno J, Carmichael B, Dunkin B, Parsons J, Smit D. 2021. Can nuclear batteries be economically competitive in large markets? Energies (in review).

Reyes JN Jr, Southworth F, Woods BG. 2020. Why the unique safety features of advanced reactors matter. The Bridge 50(3):45–51.

Smith AB. 2021. 2020 US billion-dollar weather and climate disasters in historical context. NOAA Climate.gov, Jan 8.

WNA [World Nuclear Association]. 2017. Transport of radioactive materials. London.

An Interview with . . .

Ken Goldberg, Engineering Professor and Artist, UC Berkeley

RON LATANISION (RML): We're delighted you're joining us today, Ken. I think this will be our first interview with an artist-engineer.

KEN GOLDBERG: It's a pleasure to talk with you and Cameron!

I've been lucky to pursue research and art relating to robots for 25 years at UC Berkeley. This campus seems to attenuate the long history of friction between the arts and sciences. In 1959 physicist and novelist C.P. Snow presented a lecture at Cambridge on "The Two Cultures." He had friends in both fields, but they never talked and had somewhat of a disdain for each other. Many who read this may relate to that. Many scientists view artists as soft and fuzzy, and artists think of scientists as clueless about history and culture. There are some who fit those descriptions, but most artists are very rigorous and most scientists care deeply about history and culture. But this misunderstanding is still very persistent and prevents people in the arts and sciences from interacting more constructively.

RML: That's interesting. My experience with many of my academic friends is that a number of them are musicians, even accomplished musicians. One of my friends at MIT was involved in electronics and semiconductor physics, and he used to put together a quartet of members of the Boston Symphony Orchestra whom he knew. He played the piano and flute and he would have three musicians come out, invite his friends to his home, which he had designed for music, and we would enjoy the evening together.

But it's true I don't know that many artists. I think there is a lot of misunderstanding and perhaps just not much conversation.

DR. GOLDBERG: Good point: music, more than other art forms, is more closely aligned with mathematics and engineering. But there's a persistent tendency among scientists to dismiss visual art, in particular modern and contemporary sculpture and painting as being frivolous. It's not obvious why a banana duct-taped to a wall sells for $120,000, but there are good reasons….

CAMERON FLETCHER (CHF): Ken, you mentioned the "rigor" of art. For the benefit of readers who may not understand that will you explain it, please?

DR. GOLDBERG: Yes: the amount of hard work and studying that's needed to learn how to be an artist is analogous to the hard work that we're well aware of in engineering—learning calculus and physics over years of intensive time and effort.

Successful artists must study deeply to understand how art works. They have to learn about the logic, language, and very nuanced complexity of thousands of works of art. In art and science, you can't innovate if you don't

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Ken Goldberg holds the William S. Floyd Jr. Distinguished Chair in Engineering at UC Berkeley and is chief scientist at Ambi Robotics. He is professor of industrial engineering/operations research (IEOR) with joint appointments in EECS, art practice, the School of Information, and, at UCSF, radiation oncology. His artwork is represented by the Catharine Clark Gallery in San Francisco. This interview took place February 19, 2021. It has been edited for length and clarity.

understand what has gone before. Art has a logic and a complexity that's very analogous to engineering.

RML: I understand you grew up in Bethlehem, Pennsylvania. My wife grew up there and there are a couple of interesting coincidences. What you just said about rigor and comprehension and so on struck a chord. You mentioned that when you were in high school you told your parents you were interested in art and they suggested you study something more practical. That's exactly what my wife Carolyn has said. She's mostly a watercolor artist, but her parents convinced her that she should become a teacher, and she got a degree in art education.

Now, here's the connection to what you were saying. Carolyn grew up right near Bethlehem Steel, Montclair Avenue, the south side. Everybody in her family worked there. For her, the steel company was smelly, noisy, and dirty.

As an engineering undergraduate I spent a lot of time with artists, poets, and philosophers, which had a huge influence on me.

But when the company announced it was going to go out of business, she became very nostalgic and arranged 3 weeks of tours through the mill to take photographs, which she subsequently painted. I'm amazed by how much she learned about the technology of steel making during that 3-week period. You can see it, and the connection between her art and the technology is fascinating to me because I had never seen that in her work before.

DR. GOLDBERG: I'm also nostalgic about the glory days of Bethlehem Steel. I would love to see Carolyn's paintings.[1]

RML: How did you go from your interest in art to a BS in electrical engineering at Penn?

[1] Carolyn Latanision's series of Bethlehem Steel watercolor paintings can be viewed at https://www.carolynlatanision.com/project/bethlehem-steel/.

DR. GOLDBERG: My father was a metallurgical engineer and he had an interest in art all his life. When he was in college at UPenn, he sold paintings and prints to make pocket money. My mother was studying psychology and they both had an interest in art. They would go to the Philadelphia Art Museum and had this whole romantic connection over that. When I was growing up, my parents would take me to museums in New York and Philadelphia.

But they were very practical, and strongly recommended that I get an engineering degree: 'You'll always have a job, and then you can make art.'

RML: You obviously do both supremely well in terms of your academics and the awards you've won and the recognition you've gotten. Do you describe yourself to friends as an artist or an engineer?

DR. GOLDBERG: That depends on which friends. As an engineering undergraduate I spent a lot of time with artists, poets, and philosophers, which had a huge influence on me. I had friends who were engineers and friends who were artists, but they rarely spent time together. I appreciated and respected all of them for their intelligence and insights. I liked being surrounded by a diverse group of smart and creative people; that's why I wanted to pursue a career in academia.

Since I was a kid, I'd been building rockets and robots, and in college I discovered the field of robotics, where engineers investigate the mind-body problem.

Soon after I joined the computer science faculty at the University of Southern California (USC), I established my robotics research lab and met the senior curator of the university art gallery. She introduced me to Margaret Lazzari, a young professor of painting, and said, 'I think you two will get along. If you can come up with an installation I'll host it in the university museum.'

We connected immediately and collaborated on a large solo installation about the history of Los Angeles called *Power and Water*. At the opening, a senior colleague from engineering pulled me aside and said, 'Listen, this is…not going to get you tenure…. you should stop doing it.'

So I went underground—I kept making and exhibiting art but I didn't talk about it on campus and I had two CVs, one for engineering and one for art. In engineering I focused on geometric algorithms for robotics, publishing papers and patents with my students. When I moved to Berkeley and came up for tenure, I submitted only the engineering CV. A year later, a senior colleague told me

Power and Water Installation by Ken Goldberg and Margaret Lazzari, 1992.

it was now okay to "come out of the closet." So I merged my CVs.

I was afraid of being judged in the ways C.P. Snow described in "The Two Cultures." But I've learned that Berkeley is a very diverse intellectual environment where scientists and artists often hang out together in cafés.

I started a lecture series that we named—a bit ambitiously—the Art, Technology, and Culture Colloquium. The idea was to host a speaker one evening every month to present current ideas at the intersection of art, technology, and culture.

We started it on a shoestring. We would buy some pretzels and beer and people ended up hanging out in the hallway long after the talk, and then we started going to a bar afterward to continue the conversations. It's been going on now for 24 years.

CHF: How wonderful. Is this the series for which you've had Laurie Anderson and David Byrne?

DR. GOLDBERG: Yes, and Vito Acconci, Sophie Calle, Gary Hill, Pierre Huyghe, Miranda July, Billy Kluver, and Bruno Latour.

CHF: I wish I could attend those lectures.

DR. GOLDBERG: You can! Most of them are online at http://atc.berkeley.edu.

CHF: Have any of these talks informed your work in any way?

DR. GOLDBERG: Definitely. I've attended all 220 lectures and have learned from every one. I continue to learn new ways to present ideas to each unique audience.

RML: Engineering obviously informs your art. Does art inform your engineering research?

DR. GOLDBERG: Absolutely. My work as an artist encourages me to challenge assumptions and to pursue unorthodox ideas. The public has many misperceptions about robotics and artificial intelligence. I feel it's my duty to critique the exaggerations and misperceptions. And to critique the arrogance of the world of engineering, which tends to believe that it knows best.

I try to bring a sense of humility to my artwork. Viewers have to be drawn into an artwork, you can't hit them over the head.

CHF: When you're describing your TeleGarden project to engineers, do you do a little cross-pollination, introducing some historical and cultural dimensions of the project in your presentations with engineers?

DR. GOLDBERG: That's an excellent question, and cross-pollination is a great word for it. I do my best to include some art in every engineering paper we publish.

People of diverse backgrounds should be involved at every stage of research.

I have a rule in the lab: every slide must include an image. Images can always illustrate intuition.

In art and research, it is essential to innovate. Duchamp can place a shovel against the wall and declare that it is art. But the second person who places a shovel against the wall doesn't get credit, and that's equally true for engineers and scientists.

Art is about creativity and innovation. Similarly, to publish a paper in engineering or science, you've got to demonstrate something truly new.

CHF: I love what you said about insisting that your students incorporate an image, because it reminds me of that book, *Drawing on the Right Side of the Brain.* To compel engineers and scientists to incorporate an image, especially if it's more symbolic than explicitly representative, is a way to engage a different part of the brain.

RML: I think that's right, Cameron, and I think there's another dimension. What you've described, Ken, sounds like you're kind of humanizing engineering. The average person in the street doesn't really understand engineering. They have cell phones and laptops and everything else. They understand that technology is part of their lives, but it's not humanized. It's a convenience, something they use, sometimes not for good purposes. But with what you're doing, I think you're adding a dose of humanity that is otherwise absent in engineering education. I think that's quite important.

DR. GOLDBERG: The human aspect of engineering is often overlooked. As engineers, we know the agony of an experiment not working, and the amazing feeling of working all night on a proof and having it fall into place. These are thrilling moments, and it takes a fair amount of preparation to get there.

RML: I think we might be on the cusp of changes in science and technology and engineering in the United States. I'm thinking particularly of the recent appointments to the Office of Science and Technology Policy by President Biden. He included some very distinguished people, and the one that most stands out to me is a social scientist from Princeton, Alondra Nelson. There's never been a social scientist at OSTP to my knowledge.

Engineers develop technology that is supposed to serve a social purpose, but we rarely ask, Is it really beneficial? What are the limits? What are the unintended consequences? How should we respond to new technology? Is it just based on the economic potential of a new development, or is there something more human that should be considered?

So I think having a social scientist at OSTP is really important. Given our conversation, I wonder whether there ought to be someone maybe from the humanities or the arts at OSTP.

DR. GOLDBERG: That could open new doors. OSTP might also bring in a historian.… We should involve diverse perspectives in every step of technological process—asking questions, challenging what's being done, identifying nuances and subtleties. People of diverse backgrounds should be involved at every stage of research.

RML: That's a good point. Let me ask you about another item. Can you tell us about AFRON, the African Robotic Network?

DR. GOLDBERG: In the 1960s my parents were idealistic students at UPenn engaged with the civil rights movement. They traveled to the South and were involved in sit-ins. When they graduated they found a teacher at a progressive school in Nigeria who taught in English and he invited them to work there for 2 years. They moved to a very small village near Lagos. There was no running water. There was a generator but no steady electricity. My father taught physics, my mother taught English, and they decided to have a child because they had all this time on their hands, so I was born there in 1961.

CHF: How long did you live there?

DR. GOLDBERG: Six months. It was very hot and there were a lot of mosquitoes and a lot of challenges to have a baby in that environment. So my parents finished their 2 years—just as the Peace Corps started—and came back to the States.

That influence of Africa has always been important to me. My parents would talk about Africa, and we had a lot of African artifacts around the house.

Prizewinning Lollybot, created by Tom Tilley for the 2012 inaugural competition of the African Robotics Network to build a robot for $10. Photo credit: Ann Tilley.

Five years ago I went with my mother to Ghana. We had arranged to meet some professors at Ashesi University, a new, very progressive university. One of them, Ayorkor Korsah, taught robotics and she and I became close friends. We had both gone to Carnegie Mellon so we had that in common. After meeting her students and talking she and I decided to start the African Robotics Network and bring together engineers across Africa who are interested in robotics—we saw that the students were engaged and interested in robots, as are kids all over the world.

The problem is that the robots that were available were very expensive. You can buy a Lego kit for $300. Many Americans have one; but in Africa one kit was passed around—shared by dozens of schools.

Our goal was to design an ultra-affordable robot for education. We set an ambitious target, which we thought would never be accomplished: Could someone design a robot that costs only $10.00 but is programmable and can actually teach you about real robotics?

We raised some money from the IEEE and we announced this competition, and we got 40 submissions from all over the world—India, China, Africa, Brazil—and they were really interesting, beautiful designs. But they all ranged from about $100 to $150. Only one met our cost limit—and the design just blew our minds.

There was a hobbyist who lived in Thailand, Tom Tilley. In his spare time he liked to take old game controllers apart and repurpose them. He had taken apart the controller for the Sony game and attached wheels to it. He needed a counterweight, so he looked around and decided brilliantly to insert two lollipops. What he later called the Lollybot would drive around and when it bumped into a wall the lollipops would tilt forward, activate the thumbswitches, and stop the robot. The videos are amazing. He has online the whole detail on how to make your own.[2]

Sony game controllers are essentially in landfills now, they are so widespread and everybody has moved on, but they are available for about $3.00 almost anywhere, and the whole cost of making this robot was $8.64.

[2] https://tomtilley.net/projects/lollybot/

A student from Nigeria, Simeon Adebola, competed in that competition, and he'll join my lab as a PhD student this fall.

RML: That's wonderful! While preparing for our conversation today I watched "Why We Love Robots," which you and your wife Tiffany put together. She's a producer and director of films, is that correct?

DR. GOLDBERG: Yes. I'm so glad you mentioned her. Tiffany's father Leonard Shlain was a surgeon, very well known in the Bay area, and in his spare time he was a writer and he wrote a book called *Art and Physics*.

Chapter by chapter he went through the parallels of what was happening in science and art. For example, he wrote about Einstein's idea of light bending in the context of cubism and how artists—cubists and Picasso and others—and the general law of relativity were happening simultaneously in the first decade of the 20th century—and he saw that there were symmetries. In some ways the artists were even a little ahead of the engineers or the scientists. It's a wonderful book.

Here's the amazing thing. He was a surgeon, not a physicist, not an artist, but he wrote this audacious book that speaks to both.

> *Cubist art and the law of relativity emerged simultaneously in the first decade of the 20th century—they had surprising parallels.*

At the time I was teaching at USC, I got phone calls from five friends saying, 'Have you seen this book?' I rushed out to buy a copy and devoured it. I still remember thinking 'how did this surgeon write so attentively about physics and art?'

Five years later I was at UC Berkeley and a friend called and said, 'Hey, there's a lecture tonight by this speaker I think you might be interested in. His name is Leonard Shlain.'

It was in 1997, January 24th, a rainy night. As I was going into the gallery I met Dr. Shlain and offered to help carry some of his books up to the gallery. I mentioned that I was an artist and an engineer and that I teach at Berkeley. And he said, 'Oh, have you met my daughter?'

We met that night and fell madly in love. Tiffany and her father were very close, and of course he approved because I was at his lecture. We have been living happily ever after.

RML: That is a great story. I do want to ask you about "Why We Love Robots."[3] You were nominated for an Emmy, which is interesting for an engineer to have that experience. When you and Tiffany put this together, you were both on screen. Did you collaborate on the script? Tell us about "Why We Love Robots" and how it evolved.

DR. GOLDBERG: We were cowriters and I really enjoyed the collaboration. It brought out the side of me that's interested in thinking more culturally and broadly about topics.

She was the founder of the Webby Awards, the Oscars of the internet. The first Webby Awards was about a month after we started dating.

She was doing a series on the future and culture and she had a number of episodes to write. We did two together, and one of them was "Why We Love Robots," addressing misperceptions about robots, going back to the ancient Greeks and to Frankenstein.

RML: Well, you guys really nailed it. From another perspective, a lot of people who think about AI and robots are concerned about robots taking away jobs. You've addressed that in some of your videos. What would you tell our readers about that? How would a congressman, for example, address a constituent who is concerned that technology is taking away jobs?

DR. GOLDBERG: I think it's very important to understand that this fear of someone coming to take your job is a very old fear that is analogous to the fear that an immigrant will take your job. The language used is analogous to people worried at the turn of the century about Asian immigrants taking over jobs. Oliver Morton did a wonderful piece in the *Economist*, noting that robots are immigrants—not from another country, but from the future.[4]

I want to reassure everyone that this is not something to worry about right now. Robots are not going to steal your job, and here is the reason: It's very hard to repro-

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[3] https://www.youtube.com/watch?v=owoKAzD-Ues

[4] Morton O. 2014. Immigrants from the future. The Economist, Mar 27.

The Telegarden (1995–2004), networked art installation at the Ars Electronica Museum, Austria.

duce the physical abilities, dexterity, and perception of humans.

The first step of any robot for many, many jobs is to be able to pick things up, but robots are still remarkably clumsy. Even something as simple as clearing the dinner table is far beyond the capacity of today's robots. I've been studying this problem for 35 years, and we have made amazingly little progress. It seems trivial—a 1-year-old child can do it, but a robot cannot. For example, if there's some glassware on the table, the robot can't perceive it. If there are shiny forks and spoons, they will be very confusing to a robot. There are a lot of nuances.

There's talk about robot drivers taking over, about autonomous vehicles, and I can tell you that this is mostly science fiction. We are very far from autonomous taxis in an urban setting—I believe that's many decades away.

There is a persistent fear that technology is going to destroy us. But humans have lived through so much and we are resilient. Covid-19 is a good illustration of our resilience. So I am optimistic.

I can share the story behind our best-known installation: the Telegarden. When the internet first came out I was on the faculty at USC and, as I mentioned, doing artwork underground while I was teaching and doing research. When it came out in 1993, I saw that the internet had great potential, and my students and I wanted to work on it and contribute. We decided to connect a robot to the internet.

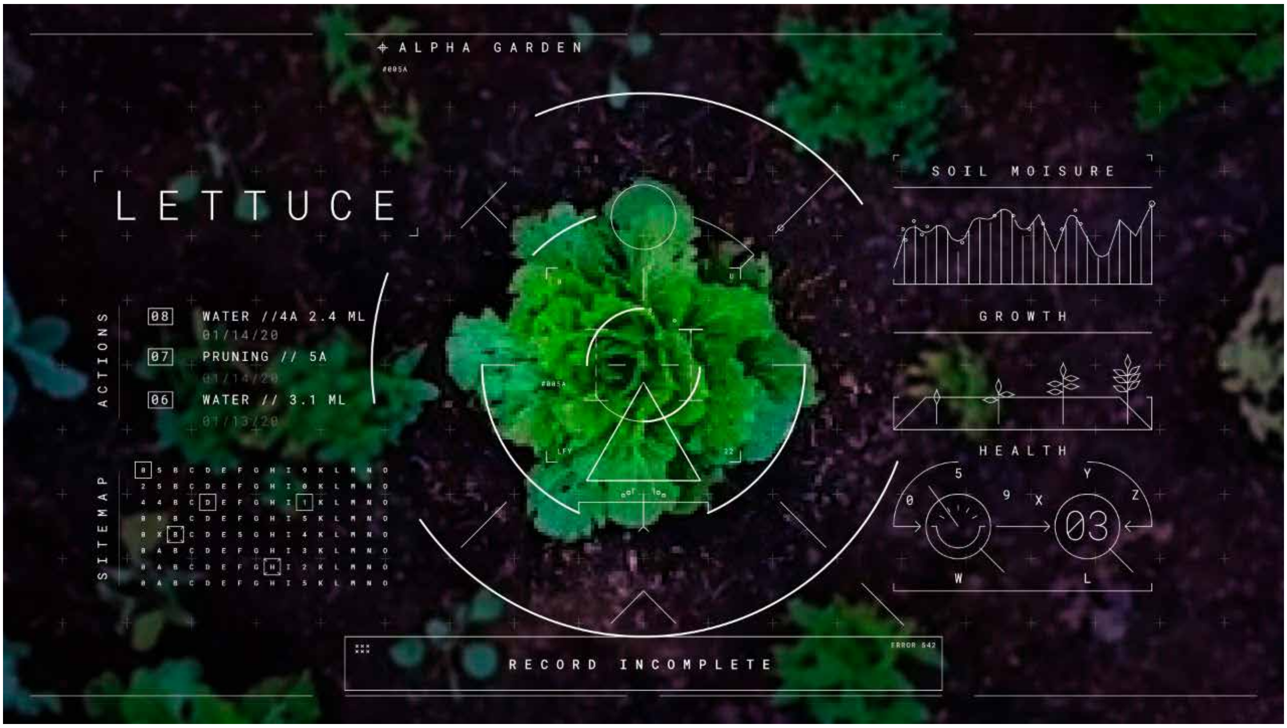
We had an IBM robot in the lab and we started thinking 'How do we interface it? How do we get it to work 24 hours a day unattended?' That was a big challenge. And we wanted to make sure that someone couldn't break it, so we had to think about security.

But we also wanted something that would bring people in and would be a compelling application. What would people want to do over the internet? The artist in me said, 'What will people *not* want to do over the internet? What is something that's a kind of absurd application?' We came up with the idea of a living garden where people could plant and water seeds over the internet.

To my mind it was something that people could relate to, and at the same time a bit of a critique—people have been planting seeds for 10,000 years, and it's hubris to put a robot in the middle of a living garden. I thought, 'The contrast between those two worlds is going to be very interesting.' I was curious to see what would happen.

It was hugely popular. It was covered on CBS News and in *Newsweek* and the *London Times*. It became a sensation in 1995. It was the first robot that was attached to the internet, and anybody from anywhere in the world with an internet browser could come in and operate the robot 24 hours a day. The Telegarden was online for 9 years, in the Ars Electronica Museum in Austria. We believe that robot was controlled by more people than any other robot in history, approximately 100,000 people.

I invited six artists, six philosophers, and six engineers to contribute essays to a collection published by MIT Press in 2000, *The Robot in the Garden*. It explores the social and physical aspects of the contrast between the digital and the natural world. A lot of the issues



Screenshot of AlphaGarden, showing head of lettuce and criteria such as the status of its soil moisture and health, January 13, 2020.

that we wrestled with are—even more—relevant today.

In fall 2019, I had been thinking about a sequel to the Telegarden. I didn't want to redo the same project. The internet has been absorbed into popular culture; the new technology is artificial intelligence, so the new question became, Could a robot learn to tend a garden without human intervention?

This project is called the AlphaGarden—it's a reference to AlphaGo, which learns and plays the game of Go completely autonomously.

As in the Telegarden, the artist in me was secretly rooting for the natural world. I want to show that the natural look is so much more rich and complex and nuanced. It's very hard to learn how to tend a garden, and in particular a polyculture garden with different kinds of plants growing in close proximity.

The AlphaGarden is still ongoing. It was featured in an exhibit in New York City just before the pandemic. The garden was in our greenhouse at Berkeley with a robot sitting beside it and a camera so people could view it online. When covid-19 struck we were denied access to the greenhouse; we couldn't go in and control the water, so over the next 6 weeks we watched helplessly from the camera as the garden died.

It was incredibly poignant. We took time-lapsed photos. The garden struggled the last few weeks, sending out flowers and shoots and reaching out desperately. It reminded me of Picasso's *Guernica* because it's that same kind of struggle. The garden was desperate for help, for attention, so it sent out these flowers at the very end.

To me that was the most interesting aspect, nature doing all these remarkable, unexpected things when it was put under stress.

RML: That is quite a story. Ken, this has been a terrific conversation. I've enjoyed it enormously. Thank you very much.

DR. GOLDBERG: Thank you so much. I appreciate your asking me. I love talking with you two. We have to get together in Washington sometime when this whole thing is over.

RML: That's a wonderful idea.

DR. GOLDBERG: Your questions really inspired me this morning. I have loved the conversation, and thank you so much for the opportunity.

CHF: It was a treat for us. Thanks again, Ken. Take good care.

NAE News and Notes

NAE Newsmakers

Alfred V. Aho, Lawrence Gussman Professor, Columbia University, and **Jeffrey D. Ullman**, Stanford W. Ascherman Professor of Engineering Emeritus, Stanford University, have received the **2020 A.M. Turing Award**—widely considered the "Nobel Prize of computing"—for their influential work in algorithms and compilers. The award citation reads "For fundamental algorithms and theory underlying programming language implementation and for synthesizing these results and those of others in their highly influential books, which educated generations of computer scientists."

Gilda A. Barabino, president of Olin College of Engineering, is **president-elect of the American Association for the Advancement of Science**. Dr. Barabino is an internationally recognized thought leader and highly sought speaker and consultant on race/ethnicity and gender in science and engineering, with particular focus on creating cultures and climates that support a sense of belonging. She has led a number of initiatives in these areas including serving as the founder and executive director of the National Institute for Faculty Equity. She assumed her role as president-elect in February and will become AAAS president in February 2022 and chair of the board of directors in February 2023.

The **National Mining Hall of Fame** has announced its **2021 inductees**. **Gary J. Goldberg**, director, BHP Group Limited, and **Raja V. Ramani**, professor emeritus, George H. Jr. & Anne B. Deike Chair in Mining Engineering, Pennsylvania State University, were among the four individuals so honored. The National Mining Hall of Fame and Museum is a federally chartered memorial for men and women who have achieved lasting greatness in the mining industry and related fields.

C.D. Mote Jr., Regents Professor, University of Maryland, and former NAE president, has received the **2021 Benjamin Franklin Medal in Mechanical Engineering** "For his outstanding contributions, through application of theory, analysis, and inventive experimentation, to the understanding of the dynamics of practical systems such as saws, skis, and conveyor belts, thereby increasing their safety, efficiency, and economy."

Linda R. Petzold, professor, Department of Mechanical Engineering and Department of Computer Science at the University of California, Santa Barbara, has been named a **fellow of the American Institute for Medical and Biological Engineering** (AIMBE) in recognition of her interdisciplinary achievements. Professor Petzold is widely recognized for her impactful work on mathematical modeling and computational simulation in a variety of disciplines and applications. Her breakthrough 1982 paper "Differential-algebraic equations (DAEs) are not ODEs [ordinary differential equations]" opened up a new subfield in computational mathematics, and her public-domain software DASSL has enabled the simulation of countless systems in engineering and science.

George M. Pharr IV, professor in the Department of Materials Science and Engineering at Texas A&M University, has been recognized by the Minerals, Metals and Materials Society (TMS) with the **2021 William D. Nix Award** "for development of methods for the quantitative determination of material mechanical response by nanoindentation and its use to elucidate fundamental mechanisms of material behavior." Professor Pharr will present a lecture on his research at the March 2022 TMS meeting to be held in Anaheim, California.

Maxine L. Savitz, retired general manager, Technology/Partnerships, Honeywell Inc., has been selected as a **2021 IEEE HKN Eminent Member**. Eta Kappa Nu established the Eminent Member recognition in 1950 as the society's highest membership classification, conferred on those whose attainments and contributions to society through leadership in the fields of electrical and computer engineering have resulted in significant benefits to humankind. Only 143 individuals have been selected for this honor.

John A. Swanson, University Support, University of Pittsburgh, Cornell University, and University of South Florida, will be honored with the **2021 Cornell Engineering Distinguished Alumni Award** in recognition of his extraordinary leadership, vision, and the distinction he has brought to the college.

The award will be presented October 14 in an on-campus ceremony.

On April 26 the National Academy of Sciences announced the election of 120 new members. Among them were 10 NAE members: **Donna G. Blackmond**, professor and chair, Department of Chemistry, Scripps Research Institute, La Jolla, CA; **C. Jeffrey Brinker**, laboratory fellow, Sandia National Laboratories, and Distinguished and Regent's Professor, Department of Chemical and Biological Engineering, University of New Mexico, Albuquerque; **Glenn H. Fredrickson**, Mitsubishi Chemical Chair in Functional Materials, Department of Chemical Engineering, University of California, Santa Barbara; **Cato Laurencin**, University Professor and Albert and Wilda Van Dusen Distinguished Professor of Orthopaedic Surgery, University of Connecticut Health Center, Farmington; **Yann LeCun**, vice president and chief artificial intelligent scientist, Facebook, and Silver Professor of Computer Science, Data Science, Neural Science, and Electrical and Computer Engineering, New York University; **Linda Petzold**, professor, Department of Mechanical Engineering and Department of Computer Science, University of California, Santa Barbara; **J. Marshall Shepherd**, Georgia Athletic Association Distinguished Professor and director, UGA Atmospheric Sciences Program, University of Georgia, Athens; **Michael E. Cates**, Lucasian Professor of Mathematics and Royal Society Research Professor, University of Cambridge; **Claudia A. Felser**, director, Max Planck Institute for Chemical Physics of Solids; and **Viola Vogel**, professor, Department of Health Sciences and Technology, and head, Laboratory of Applied Mechanobiology, ETH Zürich. **Marshall Shepherd** has the distinction of being the second person to be elected to the NAE, NAS, and American Academy of Arts and Sciences in the same year; the first NAE member thus recognized was Jean Fréchet in 2000.

The **American Academy of Arts and Sciences** has announced **new members elected in 2021**. They include **Zhenan Bao**, professor of chemical engineering, Stanford University; **Gilda A. Barabino**, president and professor of biomedical and chemical engineering, Olin College of Engineering; **Linda J. Broadbelt**, Sarah Rebecca Roland Professor and associate dean for research, Northwestern University; **Linda G. Griffith**, professor of biological engineering and mechanical engineering chair, Massachusetts Institute of Technology; **Jeffrey A. Hubbell**, Eugene Bell Professor in Tissue Engineering, University of Chicago; **R. Vijay Kumar**, Nemirovsky Family Dean, University of Pennsylvania; **Fei-Fei Li**, professor, Computer Science Department, and codirector, Stanford Institute of Human-Centered AI (HAI), Stanford University; **Muriel Médard**, Cecil H. Green Professor, Massachusetts Institute of Technology; **Teresa H. Meng**, Reid Weaver Dennis Professor Emerita, Department of Electrical Engineering, Stanford University; **Margo I. Seltzer**, Canada 150 Research Chair & Cheriton Family Chair, Computer Science, University of British Columbia; **J. Marshall Shepherd**, Georgia Athletic Association Distinguished Professor and director, UGA Atmospheric Sciences Program, University of Georgia, Athens; **Daniel A. Spielman**, Henry Ford II Professor of Computer Science and Statistics and Data Science, Yale University; and **Esther S. Takeuchi**, chief scientist, Energy Sciences Directorate, Brookhaven National Laboratory, and SUNY Distinguished Professor, Materials Science & Engineering, & Chemistry, Advanced Energy Research and Tech Center, Stony Brook University.

The VinFuture Foundation has established a new award, the **VinFuture Grand Prize**, to inspire and support the world's brightest minds to focus on using science and technology to solve the toughest global challenges. The prize will honor exceptional minds whose breakthrough scientific research and technological innovations have the potential to create meaningful change at scale. The VinFuture Prize Council is an international group of distinguished individuals from academia, research, and industry, renowned for their achievements and contributions in science, technology, and industry in advancing human progress. **Richard H. Friend**, Cavendish Professor of Physics, Cavendish Laboratory, University of Cambridge, chairs the prize council, and **Gérard A. Mourou**, director, IZEST-DGAR, Ecole Polytechnique, is a council member.

NAE Treasurer and Councillors Elected

This spring the NAE elected its treasurer and reelected four incumbent councillors. All terms begin July 1, 2021.

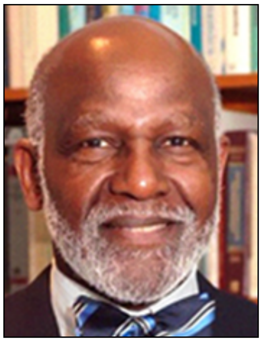
Elected to a 4-year term as NAE treasurer was **Roger L. McCarthy**, consultant with McCarthy Engineering.

Reelected as councillors are **Nadine Aubry**, provost, senior vice president, and professor of mechanical engineering, Tufts University; **Wesley L. Harris**, Charles Stark Draper Professor of Aeronautics and Astronautics, Massachusetts Institute of Technology; **Edward D. Lazowska**, professor and Bill & Melinda Gates Chair Emeritus, University of Washington; and **Howard B. Rosen**, managing director, BonVelo Ventures, and lecturer, Stanford University. All terms are 3 years.

On June 30, 2021, **Martin B. Sherwin**, retired vice president of W.R. Grace, will complete two terms of service as treasurer, the maximum allowed under the Academy's bylaws. He was recognized in May for his distinguished service and other contributions to the NAE.


Roger L. McCarthy


Nadine Aubry


Wesley L. Harris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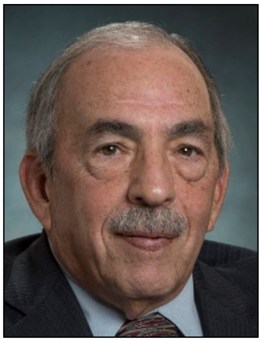

Martin B. Sherwin

Stephen D. Bechtel Jr., Former CEO of Bechtel, First Chair of the NAE Council

Civil engineer and former Bechtel CEO **Stephen D. Bechtel Jr.**, the first chair of the NAE Council, passed away March 15 at his home in San Francisco. He was 95.

Bechtel was the third-generation heir of the Bechtel Corp. construction empire and led the company for 30 years. According to Bechtel Corp.'s website, he doubled the company's size in less than 2 decades. As an engineer and the leader of one of the nation's foremost engineering and construction firms, he directly contributed to building the US industrial base and improving quality of life for millions of people.

He oversaw contracts for the Bay Area transit system, California's San Onofre Nuclear Generating Station, and the $30 billion Jubail Industrial City in Saudi Arabia, which was heralded as the largest contemporary engineering and construction project at the time.

As a boy Bechtel would accompany his father on inspections at the Hoover Dam, a project on which the company was a lead partner. After spending his summers as a youth working as a sweeper and surveyor's stake puncher, he considered going into home construction but, when he married, his father took him and his new wife on a 3-week honeymoon cruise around the world visiting company projects. Bechtel Jr. was won over and his first job at the corporation was on a Texas pipeline where top executives tutored him.

He became president in 1960, at age 35, and chair 13 years later. He applied team management principles and, believing that collaboration inspired and motivated employees, ultimately changed the company's top-down hierarchy.

In the 1960s he helped the company secure its leadership position in power, petroleum, mining, and civil engineering. During the 1970s he guided the company into an era of international demand for technically complex, often first-of-a-kind projects. And during the 1980s he led Bechtel to develop the world's first commercial facility for converting natural gas to gasoline and the first US power plant based on coal gasification technology. He also established a corporate research and development unit that is now one of the oldest and largest of its kind in the engineering-construction industry.

Exhibiting classic traits of an engineer, he could shift easily from studying technical details to setting overall strategic goals, from dealing face-to-face with craftspeople to meeting with heads of corporations and even nations. He could offer disciplined analysis as well as inspiring encouragement.

Steve Bechtel served three US presidents: Lyndon Johnson on the President's Committee on Urban Housing; Richard Nixon on the National Industrial Pollution Control Council, the National Commission on Productivity, the Labor Management Advisory Committee, and the National Commission for Industrial Peace; and Gerald Ford on the President's Labor Management Committee.

Elected to the NAE in 1975, he served as its first chair from 1982 to 1986. His many honors included the 1982 Chairman's Medal from the American Association of Engineering Societies (AAES) and the 1997 AAES National Engineering Award. In 1991 President George H.W. Bush awarded him the National Medal of Technology, the country's highest honor for technical achievement that benefits the people of the United States.

He received his bachelor of science degree in civil engineering in 1946 from Purdue University and master's degree in business administration from the Stanford University Graduate School of Business in 1948.

Bechtel is survived by his wife of 75 years, the former Elizabeth Mead Hogan, and their five children.

President Anderson Invites Members to Speak in His Stead

NAE president **John L. Anderson** receives a number of invitations to speak at national and international conferences. If he determines that he is not sufficiently knowledgeable to give a substantive talk and properly represent the NAE, he asks an NAE member to speak in his stead. Three such opportunities have recently presented themselves.

Timothy C. Lieuwen (section 1; School of Aerospace Engineering, Georgia Institute of Technology), NAE representative on the International Council of Academies of Engineering and Technological Sciences (CAETS) Energy Committee, represented the NAE on the Pathways-to-Net-Zero Panel at a virtual seminar April 14–15 organized by Mott MacDonald.

At the annual CAETS meeting this fall, **David R. Walt** (section 2; Harvard Medical School and Brigham and Women's Hospital) will represent the NAE with a talk titled "Evaluation of covid impact." The meeting will be hosted virtually September 21–23 by the Argentinian National Academy of Engineering.

Also in September, **Eric Horvitz** (section 5; Microsoft) will address the Turing Institute's inaugural Data-Centric Engineering (DCEng) Summit: "Global dialogue on the intersection of data science and engineering," to be held virtually September 22–23.

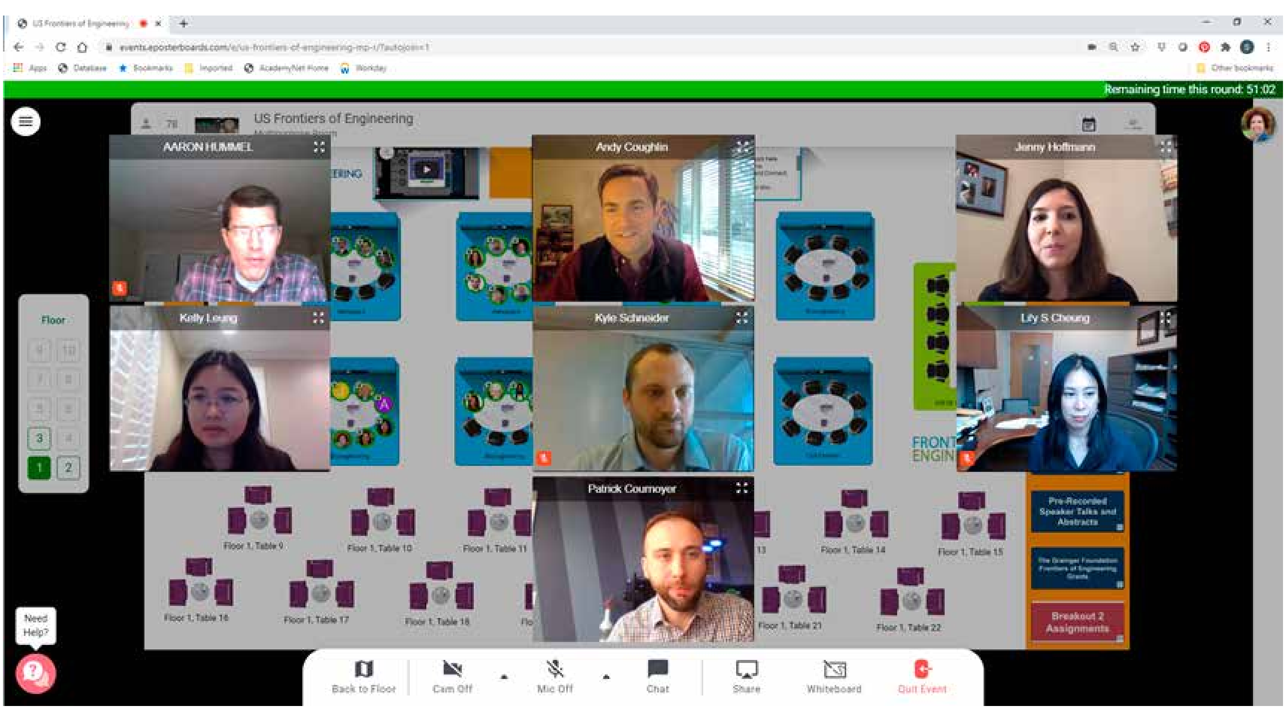
Dr. Anderson greatly appreciates members' willingness to serve the NAE in this way.

US Frontiers of Engineering Held Virtually in February

The 2020 US FOE, which is typically held in September but was postponed because of the covid-19 pandemic, was held virtually February 25–26, 2021. **Jennifer L. West**, Fitzpatrick Family University Professor of Biomedical Engineering at Duke University, chaired the organizing committee and the symposium. The sessions were Food for Thought: The AgRevolution Shaping What We (Will) Eat, Next-Generation Energy Systems Integration, Engineering Innovation in Women's Health, and Plastics: Pollution Challenges and Innovations.

By 2050 the world population is expected to increase by a third, and at the same time higher temperatures, severe weather events, and the rise of new challenges caused by climate change will affect agricultural output. Fortunately, novel technologies are being developed that are transforming what we eat, how we grow food, and what it means to be a farmer in the 21st century. The first speaker in the Food for Thought session described genome editing technologies and their application to engineer more resilient crops. This was followed by a talk on novel pest management strategies and new biologically based compounds for crop protection. The next speaker explained how the food safety of genetically modified crops and other biotechnology-derived products is ensured before they reach consumers. The session concluded with a presentation on the application of advanced robotics and automation technology to facilitate more efficient food production.

The US energy system is large and complex, includes more than electricity, and spans generation, distribution, and end use. Next-generation systems must be clean and adaptable to growing demand and new technologies. Challenges include integrating advances in optimization, computation, control, and AI to make power grids more efficient, robust, resilient, and sustainable; understanding how the energy-water nexus affects the design of future energy systems; and making energy more affordable and accessible for remote communities. Presentations in this session described the operation of future grids using new tools in control theory and AI, major energy-water dependencies such as thermal power plant cooling and water desalination, and residential-scale energy systems for Native American communities.



Screenshot of virtual USFOE.

Engineering is an integral part of healthcare innovation, yet attention to women's health has traditionally lagged. Women's health encompasses reproduction, fertility, maternal health, pregnancy, and conditions associated with birthing injuries. It also includes sex and gender differences in many diseases and pathologies, such as cancer, cardiac disease, osteoporosis, mental health, autoimmune disorders, substance abuse, and obesity. The first talk in the Engineering Innovation in Women's Health session described a low-cost, speculum-free camera device that empowers women in Africa to screen for cervical cancer. This was followed by a talk on research into the biomechanics of the reproductive tract, to advance understanding of the causes of preterm birth and birthing-related injuries. The next presentation covered tissue engineering of artificial ovaries, which gives hope to those wanting to grow their families. The session closed with a talk about NextGen Jane, a women's health startup that uses data-driven resources so women can track their health using their menstrual blood.

The universal use of plastic has resulted in contamination in every corner of the globe; microplastic in particular is transported by air and water to remote locations of the planet. We see the toxic impacts on animals such as sea birds, turtles, and whales, but we don't yet understand what this means for humans or the implications for global ecosystems. The session "Plastics: Pollution Challenges and Innovations" outlined the efforts of engineers and scientists to mitigate these issues. Presentations covered the extent and impact of plastic contamination and the importance of citizen science and open data to hold polluters responsible; the necessity of environmental degradability as a design metric; and plastic "offset" technology to fund the informal waste sector in India as a mechanism for addressing environmental and social justice issues related to plastic pollution.

Every attempt was made to create an experience for attendees that allowed for the personal interactions that are such an integral part of Frontiers of Engineering symposia. To that end, staff selected a virtual conference platform that enabled attendees to move around floor plans for a lobby, lecture hall, poster hall, and multipurpose room. Presentations were recorded in advance and available to attendees before the live event to provide more time for discussion, networking sessions, breakout groups, and happy hours. Many of the presentations are available for public viewing at the 2020 US FOE List of Sessions at www.naefrontiers.org.

Participants at this year's meeting will be eligible to apply for The Grainger Foundation Frontiers of Engineering Grants, which provide seed funding for US FOE participants who are at US-based institutions. These grants enable further pursuit of important new interdisciplinary research and projects stimulated by the US FOE symposia.

Jennifer West has served her third and final year as chair for the US FOE, and we are grateful for her service. **Timothy Lieuwen**, Regents' Professor and David S. Lewis Jr. Chair of the Daniel Guggenheim School of Aerospace Engineering at Georgia Institute of Technology, will chair the 2021 US FOE, which will be hosted by the University of Colorado Boulder, September 22–24, if the event is held in person. The 2021 topics are Resilience in Pandemics: Data and Digital Infrastructure for Informed Decision Making, Cybersecurity of Critical Infrastructure, Transforming the Climate Change Discussion: The Role of Direct Air Capture, and Investigating the Final Frontier: Engineering the Future of Space Exploration.

Funding for the 2020 US Frontiers of Engineering symposium was provided by The Grainger Foundation, National Science Foundation, Defense Advanced Research Projects Agency, Air Force Office of Scientific Research, DOD ASDR&E-Laboratories Office, Microsoft Research, Amazon, Cummins Inc., and individual donors.

The NAE has been hosting an annual US Frontiers of Engineering meeting since 1995, and also has bilateral programs with Germany, Japan, China, and the European Union. The meetings bring together highly accomplished engineers from industry, academia, and government at a relatively early point in their careers, providing an opportunity for them to learn about developments, techniques, and approaches at the forefront of fields other than their own, which is increasingly important as engineering has become more interdisciplinary. Each meeting also facilitates the establishment of contacts and collaboration among the next generation of engineering leaders.

For more information about the symposium series, visit www.naefrontiers.org or contact Janet Hunziker at JHunziker@nae.edu.

2021 German-American Frontiers of Engineering Held in March

The 2021 German-American Frontiers of Engineering Symposium (GAFOE) was held virtually March 17–19. NAE partners with the Alexander von Humboldt Foundation (AvH) to organize this event, which was started in 1998. The symposium organizing committee was cochaired by **Cynthia Hipwell**, Oscar S. Wyatt Jr. '45 Chair II Professor in the J. Mike Walker '66 Department of Mechanical Engineering at Texas A&M University, and Olivier Guillon, director of the Institute of Energy and Climate Research at Forschungszentrum Jülich GmbH.

Modeled on the US Frontiers of Engineering Symposium, GAFOE brings together 60 early-career engineers from German and US companies, universities, and government. The goal of the meeting is to convene emerging engineering leaders in a forum where they can learn about leading-edge developments in a range of engineering fields, facilitating an interdisciplinary transfer of knowledge and methodology. In the case of the bilateral Frontiers, there is the added dimension of helping build cooperative networks of young engineers that cross national boundaries.

The four session topics at this year's GAFOE symposium were Quantum Computing, Carbon Capture and Utilization, Biologization, and Manufacturing 4.0. The session on quantum computing highlighted how hardware breakthroughs, a focus on potential near-term applications, and industry interest have raised the profile of quantum computing. Both the promises and the challenges of quantum computing were discussed. The first presentation described how quantum computers work and their differences from classical computers. The next speaker covered the types of computational problems where quantum computers are likely to provide some advantage over classical computers. This was followed by a presentation on the challenges of building quantum hardware and a concluding talk on the uses of quantum technology outside of computation.

The buildup of CO_2 is the dominant cause of climate change; but carbon is also a useful building block for products and fuels, and fossil fuels remain an inexpensive source of stored energy. The field of carbon capture, utilization, and storage (CCUS) seeks to solve this challenge. The talks in the Carbon Capture and Utilization session covered a range of issues, including how to scale up adsorption-based systems by 2–3 orders of magnitude within short time frames to create the refinery of tomorrow; hybrid absorption-crystallization pathways to produce high-purity H_2 and accelerate carbon capture; research on electrochemical CO_2 reduction reaction; and new CO_2-based materials.

"Biologization" refers to the integration of physical forces with novel ways to control biology and the use of those principles to design engineered living systems and other structures. While synthetic biology and tissue engineering have advanced control and design of biological systems, next-level processes, approaches, and considerations must be understood to bring disruptive change to controlling biology and bioinspired design. Speakers in this session addressed synthetic genome regulation for cell and tissue engineering, material design strategies derived from functional microarchitectures in biological models, the design of polymeric regenerative hydrogel therapies, and biohybrid actuators that enable the study of neuromuscular tissues in healthy and diseased states and are then deployed as responsive actuators in engineered devices.

The final session, Manufacturing 4.0, introduced current research topics in this area in the United States and Germany. The first talk presented a vision of the "internet of production" and associated opportunities and challenges for the production industry. The next speaker focused on the current and future state of the art of additive manufacturing (AM), highlighting impacts from material and process developments, AM as a cyberphysical system, digital thread intersections, and the coupling of functional and structural materials. This was followed by a talk on the need for and development of data analytics and machine learning (ML) algorithms to optimize functions and operations of these systems. The session closed with an industry perspective on ML approaches as a key tool in automotive engineering.

NAE president **John L. Anderson** and AvH secretary-general Enno Aufderheide welcomed the group to the symposium. To accommodate multiple time zones, the meeting was held in 4-hour segments over 3 days, and presentations were available prior to the meeting to allow more time for discussion, networking, and breakout groups during the live event.

Oak Ridge National Laboratory (ORNL) was originally scheduled to host the meeting, and as a substitute for in-person tours of its facilities, the lab staff organized excellent virtual tours of the Spallation Neutron Source, Manufacturing Demonstration Facility, Carbon Fiber Technology Facility, National Center for Computational Sciences, and Oak Ridge Leadership Computing Facility. A number of FOE alumni at ORNL helped organize and lead the tours.

Funding for the meeting was provided by The Grainger Foundation, National Science Foundation, and Alexander von Humboldt Foundation. The next GAFOE meeting will be held in 2023 in Germany.

The NAE has additional bilateral Frontiers of Engineering programs with Japan, China, and the European Union. FOE meetings bring together outstanding engineers from industry, academia, and government at a relatively early point in their careers since participants are generally within 12 years of receipt of an advanced degree. The symposia provide an opportunity for them to learn about developments, techniques, and approaches at the forefront of fields other than their own, something that has become increasingly important as engineering has become more interdisciplinary. Each meeting also facilitates the establishment of contacts and collaboration among the next generation of engineering leaders.

For more information about this activity, go to www.naefrontiers.org or contact Janet Hunziker at JHunziker@nae.edu.

Director of NAE Programs Receives Prestigious Award

Guru Madhavan

Guru Madhavan, the Norman R. Augustine Senior Scholar and senior director of programs, has received the Edward Weisband Distinguished Alumnus/a Award for Public Service or Contribution to Public Affairs from the Binghamton University Alumni Association. The award recognizes one alumnus or alumna each year whose life, work, career, and contributions exemplify the highest standards of service and deepest dedication to the sustenance of the common good.

Dr. Madhavan grew up in a rural part of the southern Indian state of Tamil Nadu, near Chennai. He received his bachelor's degree in instrumentation and control systems engineering at the University of Madras, and came to the United States for his MS in biomedical engineering at Stony Brook University. He worked in industry as a researcher and product manager for various companies before continuing his education at Binghamton University, where he earned an MBA in healthcare management (2007) and PhD in biomedical engineering (2009).

He has been a technical advisor to the European Union Malaria Fund and US Department of Health and Human Services, vice president of IEEE-USA, and a founding member of the Global Young Academy, an international society of young scientists. His 2016 book *Applied Minds: How Engineers Think* (published by W.W. Norton) explains the importance of applying systems thinking to inspire breakthroughs in science and technology and has been translated into many languages.

Among numerous honors, he has received the National Academies' Innovator Award, National Academy of Medicine's Cecil Medal, AAMI–Becton Dickinson Award for Professional Achievement, and Washington Academy of Sciences' Krupsaw Award for engineering sciences and education, and he was named a distinguished young scientist by the World Economic Forum. He is an elected fellow of the American Association for the Advancement of Science and the American Institute for Medical and Biological Engineering.

For his books and lectures, he has received the IEEE-USA Award for Distinguished Literary Contributions Furthering Public Understanding and the Advancement of the Engineering Profession, and ASEE's Technological and Engineering Literacy/Philosophy of Engineering Division Meritorious Award.

Guru is the first engineer in his family and the first to immigrate to America. We are so glad he did and congratulate him on this well-deserved award.

NAE Membership Office Welcomes Three New Staff

ADONNA COX joined the Membership Office April 19 as a membership associate. She will manage member records, the directory, and section meetings. With more than 15 years of experience in member engagement, she specializes in operational excellence, long-term growth strategies, audience outreach, and customer support. She sees herself as a problem solver who doesn't shy away from a new challenge. She got her bachelor's degree in psychology from the University of Maryland Global Campus, where she also studied business. In her spare time she enjoys reading and writing, and is completing the draft of a book of short stories. She can be reached at 202.334.2261 or ACox@nae.edu.

KENNYA PORTER-EL joined the Membership Office April 12 as a membership assistant. She will manage member dues, annual meeting registration, the national meeting, and updates to NAE members' Wikipedia pages. She is highly motivated and skilled at meeting customer needs. She previously managed meetings for two associations in the DC area, the Association of American Colleges and Universities and the American Academy of Facial Plastic and Reconstructive Surgery. Kennya earned her degree in criminal investigations from Everest University–Online in Tampa. She can be reached at 202.334.2222 or KPorterEl@nae.edu.

ALEJANDRO VELAZQUEZ joined the Membership Office May 10 as a membership associate. He will support the annual member election process and manage the logistical details for election committee meetings and events. Alex most recently worked with NASEM's Office of Conference Management; his technical background and event management skills will greatly benefit our members. Alex has a degree in cybersecurity from the University of Maryland University College. He can be reached at 202.334.2282 or AVelazquez@nae.edu.

New NAE Associate Director of Development

STEPHANIE HALPERIN has joined the National Academies as the new associate director of development for the NAE. She brings years of fundraising, partnership building, and relationship management experience from the NYC development community and enjoys building relationships that make a global impact for a brighter future. She was previously senior manager, development, with Malaria No More, a globally recognized nonprofit organization with the mission to end one of the world's oldest, deadliest diseases. Before relocating to Washington, Stephanie worked in a number of capacities at New York University, where she engaged with alumni, students, business leaders, and corporate and institutional partners to raise funds while advancing the mission of this research-focused global university. She also worked in various development and engagement roles to preserve archival and historical ethnic experiences at the American Jewish Historical Society. She holds a BA in Latin American history from the University of Delaware and an MA in migration and political science from the Universitat Pompeu Fabra in Barcelona. Please join us in welcoming Stephanie. She can be reached at SHalperin@nas.edu or 202.334.1842.

NAE Donor Stories

Despite the hardship we faced in 2020, our dedicated supporters ensured that the vital work of the National Academy of Engineering continued by contributing over $9.7 million in 2020, exceeding our original goal of $7.5 million. We invited our Lincoln, Franklin, Curie, Einstein, and Heritage Society donors to tell us why they decided to make an impact through philanthropic support.

What inspired you to make this gift?

Norm Abramson '76

"In making a bequest to the NAE, as I am now in the autumn of my life, it came naturally to me that I would want to help ensure that membership-related activities would continue to be the very heart of the NAE. My wish is that all newly elected members would find as much rewarding experience and pleasure in the NAE as did my wife and I."

Cleopatra Cabuz '17 and Eugen Cabuz

"We were inspired to take responsibility for the troubles of the world and do our small part in trying to right them. We have a desire to be part of the solution. The engineering profession has brought wonders to the world—from the internal combustion engine to nuclear energy, from plastics to wireless communication, from the internet to sophisticated medical investigation tools, from artificial intelligence to virtual reality—and members of the NAE are key innovators who helped make it happen. However, we must not forget that many of these technological advances bring along global challenges—the risk of devastating destruction, pollution of air, water, and land, interference with democratic processes, further divides along geographic and demographic lines, and the fast spread of disease. The Academy, as an independent forum, is uniquely positioned to be part of the solution. Our small gift supports the NAE in addressing global societal problems."

Al Bunshaft, Senior Vice President, Dassault Systèmes

"Dassault Systèmes has had multiple employees as NAE members, including our vice chair and CEO. The NAE includes the esteemed engineering leadership of our country and the world. We feel that the NAE provides a unique and valuable forum to discuss critical topics related to engineering in the 21st century."

Why was it important for you, at this time, to make your gift?

Nicholas Donofrio '95

"Time is the issue. You never have all you want or need and you never know when there will be no more. Time for action is now."

Ming Hsieh '15 and Eva Hsieh

"It's important for scientists and engineers around the world to take immediate action to work jointly, rather than competitively, to conquer the pandemic and prevent future ones."

* *

Behind every gift is a meaningful and inspiring story. The National Academy of Engineering is grateful for the generosity of all of our donors, and we appreciate those who have decided to share their stories.

Calendar of Meetings and Events

June 23–25	Japan-America Frontiers of Engineering Symposium (virtual)
August 4–5	NAE Council Meeting Alexandria, Virginia
August 12–13	EngineerGirl Ambassadors Introductions, Expectations, and Community Building (virtual)
September 22–24	US Frontiers of Engineering (if virtual; see below)
September 23–24	EngineerGirl Ambassadors Meeting: Choosing and Designing High-Quality STEM Activities (virtual)
September 27–29	US Frontiers of Engineering Beckman Center, Irvine, California (if in person)
October 1–2	NAE Council Meeting
October 3–4	**NAE ANNUAL MEETING – save the date!**

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

In Memoriam

Isamu Akasaki, 92, professor, Meijo University, Japan, died April 7, 2021. Professor Akasaki was elected a foreign member in 2008 for contributions to the development of nitride-based semiconductor materials and optoelectronic devices.

Clarence R. Allen, 96, professor emeritus of geology and geophysics, California Institute of Technology, died January 21, 2021. Professor Allen was elected in 1976 for contributions in evaluating seismicity and fault movements leading to sound engineering practices and codes in earthquake-prone regions.

Stephen D. Bechtel Jr., 95, retired chair and senior director, Bechtel Group Inc., and NAE chair 1982–86, died March 15, 2021. Mr. Bechtel was elected in 1975 for leadership of engineers in the design and construction of energy related facilities.

David T. Blackstock, 91, professor emeritus of mechanical engineering, University of Texas at Austin, died April 30, 2021. Professor Blackstock was elected in 1992 for fundamental contributions to the principles of propagation of finite amplitude sound, and their application in various engineering fields.

Edmund M. Clarke, 75, FORE Systems University Professor of Computer Science, Carnegie Mellon University, died December 22, 2020. Professor Clarke was elected in 2005 for contributions to the formal verification of hardware and software correctness.

John L. Cleasby, 93, Anson Marston Distinguished Professor in Engineering Emeritus, Iowa State University, died March 24, 2021. Professor Cleasby was elected in 1983 for many publications contributing to the advancement of the science of water treatment and for inspirational teaching.

Malcolm R. Currie, 94, retired chair, Hughes Aircraft Company, and board of trustees, University of Southern California, died April 18, 2021. Dr. Currie was elected in 1971 for major innovations in electron devices and contributions to large systems in research and development.

Robert C. DeVries, 98, retired staff scientist, GE Corporate Research and Development, died May 3, 2021. Dr. DeVries was elected in 1998 for applications of phase equilibria to the synthesis and characterization of diamond, boron nitride, and related materials.

Peter S. Eagleson, 92, professor emeritus of civil and environmental engineering, Massachusetts Institute of Technology, died January 6, 2021. Professor Eagleson was elected in 1982 for leadership in the theoretical foundations of modern hydrology.

Francis B. Francois, 87, retired executive director, American Association of State Highway and Transportation Officials, died February 17, 2021. Mr. Francois was elected in 1999 for engineering and policy leadership in surface transportation infrastructure and research.

William L. Friend, 85, retired executive vice president, Bechtel Group Inc., and NAE treasurer 2001–09, died January 27, 2021. Dr. Friend was elected in 1993 for leadership in the development of new technologies and their application in commercial facilities.

Charles M. Geschke, 81, founder and member of the board, Adobe Systems Inc., died April 16, 2021. Dr. Geschke was elected in 1995 for contributions to the development of desk-top publishing.

Delon Hampton, 87, chair of the board, Delon Hampton & Associates Chartered, died January 14, 2021. Dr. Hampton was elected in 1992 for outstanding contributions to education and practice in geotechnical and transportation engineering, and for leadership in engineering education for minorities.

Robert W. Hellwarth, 90, George Pfleger Professor of Electrical Engineering and professor of physics, University of Southern California, died January 21, 2021. Professor Hellwarth was elected in 1977 for contributions to the understanding of quantum electronics and the invention of new laser devices.

Tatsuo Itoh, 80, Northrop Grumman Distinguished Professor of Electrical and Computer Engineering, University of California, Los Angeles, died March 4, 2021. Professor Itoh was elected in 2003 for advances in electromagnetic engineering for microwave and wireless components, circuits, and systems.

David Jenkins, 85, professor emeritus, University of California, Berkeley, died March 6, 2021. Professor Jenkins was elected in 2001 for theoretical and practical contributions to improving water quality worldwide through applied research on biological wastewater treatment processes.

Leon Keer, 86, Walter P. Murphy Professor Emeritus, Northwestern University, died January 12, 2021. Professor Keer was elected in 1997 for the application of elasticity to design problems involving contact and fracture.

Makoto Kikuchi, 86, professor emeritus, Tokai University, died November 6, 2012. Dr. Kikuchi was elected a foreign member in 1987 for pioneering contributions to research on semiconductor devices, and for leadership in introducing advanced semiconductor work into Japanese industry.

Juan C. Lasheras, 69, Stanford and Beverly Penner Professor of Applied Sciences, University of California, San Diego, died February 1, 2021.

Professor Lasheras was elected in 2012 for studies of atomization, turbulent mixing, and heat transfer and for the development of medical devices.

Kuo-Nan Liou, 76, distinguished professor of atmospheric sciences and director, Joint Institute for Regional Earth System Science and Engineering, University of California, Los Angeles, died March 20, 2021. Professor Liou was elected in 1999 for contributions in the theories of radiation transfer and light scattering, with applications to remote sensing technology and climate modeling.

Raymond C. Loehr, 89, H.M. Alharthy Centennial Chair, University of Texas at Austin, died April 15, 2021. Dr. Loehr was elected in 1983 for international leadership in research, engineering analysis, education, and management practices for solution of waste disposal problems.

Enrique A. Marcatili, 95, retired head, Photonics Research Laboratory, AT&T Bell Laboratories, died January 19, 2021. Dr. Marcatili was elected in 1976 for analysis and invention of novel electromagnetic-wave guiding structures at microwave and optical frequencies.

John C. Martin, 69, former chair and CEO, Gilead Sciences Inc., died March 31, 2021. Dr. Martin was elected in 2008 for the invention, development, and commercialization of antiviral medicines, especially treatments for HIV/AIDS.

Fujio Matsuda, 95, president emeritus, University of Hawaii System, died August 23, 2020. Dr. Matsuda was elected in 1974 for leadership in the development and operation of a statewide transportation system.

Jyotirmoy Mazumder, 69, Robert H. Lurie Professor of Mechanical Engineering, University of Michigan, died April 10, 2021. Professor Mazumder was elected in 2012 for quantitative transport modeling for laser interaction and design and commercialization of direct metal deposition machines.

Sia Nemat-Nasser, 84, distinguished professor of mechanics and materials, University of California, San Diego, died January 4, 2021. Professor Nemat-Nasser was elected in 2001 for pioneering micromechanical modeling and novel experimental evaluations of the responses and failure of modes of heterogenous solids and structures.

Harold W. Paxton, 94, US Steel University Professor Emeritus, Carnegie Mellon University, died March 9, 2021. Professor Paxton was elected in 1978 for contributions to metal science and application of this understanding to the improvement of metals and their processing.

Leslie E. Robertson, 92, director of design, See Robertson Structural Engineers LLC, died February 11, 2021. Mr. Robertson was elected in 1975 for contributions in the design of tall buildings and development and application of wind-engineering principles to tall-building design for assurance of safety and comfort of the occupants.

George W. Sutton, 93, consultant, Analysis and Applications Inc., died February 13, 2021. Dr. Sutton was elected in 1994 for contributions to ballistic missile reentry, lasers, medical devices, imaging systems, and aerooptics.

Richard D. Woods, 95, professor emeritus, civil and environmental engineering, University of Michigan, died January 28, 2021. Professor Woods was elected in 2003 for applications of soil dynamics and geotechnical earthquake engineering to the design of foundations for vibration-sensitive and vibration-robust facilities.

Invisible Bridges

Hail CESER

David A. Butler is the J. Herbert Hollomon Scholar and director of the NAE program on Cultural, Ethical, Social, and Environmental Responsibility in Engineering (CESER).

The November 1892 meeting of the American Society of Mechanical Engineers was held in New York City in the cold and snowy days following Thanksgiving. There was prosaic fare like the report from a committee on flange standardization and a talk on the experimental determination of the heat generated by oil and gas lamps.[1] However, the meeting also featured sessions that would prove to be more consequential, including a detailed description of the construction and operation of a programmable "difference engine" derived from Charles Babbage's work and "Topical Discussions and Interchange of Data."

One of these "topical discussions" posed a simple—but what now seems like a perennial—question that, given the extended account of it, must have been much on the minds of the participants: "How can the present status of the engineering profession be improved?"

At the time the field of engineering was in its adolescence in the United States. Its first formal undergraduate programs (with the exception of a long-standing military engineering major at West Point) had only been recently established and there was controversy about whether non-college-educated persons should be able to call themselves "engineers." Practitioners wanted to be recognized as professionals in the same way as those in other learned fields were, and were trying to figure out how to achieve that goal.

To that end, the leader of the discussion—Holbrook Fitz-John Porter, assistant chief mechanical engineer of the World's Columbian Exposition in Chicago—proposed that engineers borrow from more established professions and emulate their operating principles. Approaches were put forward and debated, and among these were a set of principles articulated by Robert Henry Thurston of Cornell University. He argued that, while education and practical experience were both important, "character…is the final touchstone by which the profession, like its individual members, will be judged" and that a "well-established and well-sustained professional ethic" was necessary to advance the status of the field's practitioners.

Porter concluded the colloquy by suggesting that a joint committee representing the engineering professions be established and that its duties include the development of a uniform code of ethics. Scholars point to this as the first instance in which US engineers identified the desirability of having such a code.[2]

It would, however, take 3 decades before that proposal came to fruition. This was documented in the May 1922 issue of the *Annals of the American Academy of Political and Social Science*, entitled "The Ethics of the Professions and of Business."[3] The volume included monographs on the ethical codes of medical practitioners, lawyers, accountants, journalists, ministers, teachers—and a section comprising seven papers devoted to "The Ethical Codes of the Engineers." The culminating paper of that section, "A Proposed Code of Ethics for All Engineers," was authored by Alexander Graham Christie, a Johns Hopkins University mechanical engineering professor and chair of the Joint Committee on Ethics of American Engineering Societies. Christie observed that

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[1] The following accounts of the meeting are based on the Transactions of the American Society of Mechanical Engineers, vol XIV (1893).

Inspired by the name of this quarterly, this column reflects on the practices and uses of engineering and its influences as a cultural enterprise.

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[2] Layton ET. 1986. The Revolt of the Engineers: Social Responsibility and the American Engineering Profession. Baltimore: Johns Hopkins University Press. pp. 45–46.

[3] King CL, ed. 1922. The Ethics of the Professions and of Business. Philadelphia: American Academy of Political and Social Science.

> The public knows that doctors and lawyers are bound to abide by certain recognized rules of conduct. Not finding the same character of obligations imposed upon engineers, people have failed to recognize them as members of a profession.[4]

He recounted the history of attempts to establish such codes, pointing out that while various societies had put them forward, lack of consistency among them had resulted in circumstances where conduct "forbidden in one code might be tolerated in another"—the very issue that had led to Porter's 30-years-distant recommendation to create a uniform set of standards.

The joint committee's solution to this conundrum, Christie reported, was to try to define the overarching principles that would inform all engineers' conduct, regardless of their discipline. The resulting ten precepts called for engineers to practice "in a spirit of fairness to employees and contractors [and with] fidelity to clients and employers" and to avoid engaging in conflicts of interest, misleading customers, associating with disreputable persons, or using dishonorable means to compete for work. The tenth and final precept, however, moved beyond these more business conduct–related concerns, stating (in the sexist language of that era):

> He will interest himself in the public welfare, in behalf of which he will be ready to apply his special knowledge, skill, and training for the use and benefit of mankind.

This is a remarkable statement not just for its time but for any time. It has no direct relationship with the other precepts—with practitioners' knowledge or skills, with the diligence and integrity they bring to their work, or with the duty they owe to their employer, client, or fellows. It instead has to do with the engineer's place in the world. It submits that the ethical practice of engineering is more than just the successful accomplishment of one's task: the ethical engineer must consider whether the end product meets the greater needs of society.

Other contributors to this journal section had laid the groundwork for this proposal. Carl Hering contended that the dedication to public service sprang from the nature of an engineer's work:

> As the progress of the world, the comforts of man, and his ability to produce are so very largely due to the work of the engineer, his work is of the very greatest importance; he therefore naturally interests himself also in the public welfare.[5]

According to Calvin Rice, this interest also reflected the shared, terrible experience the country had been through:

> The War brought home to us all the essential principle of the obligation of the engineer to society.[6]

The ethical practice of engineering is more than just the successful accomplishment of one's task: the ethical engineer must consider whether the end product meets the greater needs of society.

The break with earlier codes and with those of other professions was also explicit, as contributors asserted that:

> Up to within a few years all engineering codes in this country were modelled after the code of the British Institution of Civil Engineers. The remarkable fact about this code and those which grew out of it was the failure to mention the public interest as a test, if not the supreme test, of action.[7]

> A code of ethics is naturally a different matter for one who deals with the application of nature's laws of matter and energy for the benefit of mankind, than for one who deals merely with getting the largest number of dollars.[8]

[4] This and the following quotations are from Christie AG. 1922. A proposed code of ethics for all engineers. Annals of the American Academy of Political and Social Science 101(1):97–104.

[5] Hering C. 1922. Ethics of the electrical engineer. Annals of the American Academy of Political and Social Science 101(1):86–89. p. 89

[6] Rice CW. 1922. The ethics of the mechanical engineer. Annals of the American Academy of Political and Social Science 101(1):72–76. p. 73

[7] Cooke ML. 1922. Ethics and the engineering profession. Annals of the American Academy of Political and Social Science 101(1):68–72. p. 69

[8] Hering, p. 89

In the end, it was journal contributor Morris Llewellyn Cooke who put it most plainly:

> The ultimate goal here is the flatfooted declaration that good engineering must be in the public interest and, contrariwise, that any engineering which is anti-social must be bad engineering.[9]

It would take more years, and undoubtedly more arguments, before the journal authors' observations and joint committee's precepts would make it into codes of conduct for the many engineering societies, but they were in the end largely adopted. Elements of them can be seen today in declarations like the World Federation of Engineering Organizations' Model Code of Ethics, which calls on professional engineers, in the course of their engineering practice, to (among other things)

- "Practise so as to enhance the quality of life in society."
- "Create and implement engineering solutions for a sustainable future."
- "Be mindful of the economic, societal and environmental consequences of actions or projects."
- "Promote and protect the health, safety and well being of the community and the environment."[10]

The National Academy of Engineering actively supports these and other tenets of the socially responsible practice of engineering. The recently established program on Cultural, Ethical, Social, and Environmental Responsibility in Engineering (CESER) aims to (i) expand understanding of how these realms affect and are affected by the practice of engineering and (ii) promote their inclusion through engagement with engineers, educators, industry leaders, professional societies, governmental entities, and the public.

Cultural, ethical, social, and environmental considerations are not often listed among the elements that define the engineering practice. Yet they are essential to the well-informed design and implementation of new infrastructure, technologies, and products, and part and parcel of a systems approach to solving complex problems.

The perspectives articulated more than 125 years ago remain just as relevant today. Far from being a recent interest, ethical and social concerns have long been considered integral to what it means to be an engineer.

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[9] Cooke, p. 70

[10] www.wfeo.org/code-of-ethics/

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