

Fall 2007

**NOISE ENGINEERING**

The

# BRIDGE

LINKING ENGINEERING AND SOCIETY

**Noise as a Technological and Policy Challenge**

*William W. Lang and George C. Maling Jr.*

**Designing Quiet Products**

*Richard H. Lyon and David L. Bowen*

**Perception-Based Engineering:  
Integrating Human Responses into Product  
and System Design**

*Patricia Davies*

**Challenges and Promises in Mitigating  
Transportation Noise**

*Ian A. Waitz, Robert J. Bernhard, and  
Carl E. Hanson*

**Engineering Controls for Reducing  
Workplace Noise**

*Robert D. Bruce*

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*The Bridge* (USPS 551-240) is published quarterly by the National Academy of Engineering, 2101 Constitution Avenue, N.W., Washington, DC 20418. Periodicals postage paid at Washington, DC.

Vol. 37, No. 3, Fall 2007

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

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

*The Bridge* is printed on recycled paper. ♻️

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### Correction

June issue, page 43. The Frontiers of Engineering Program was started in 1994 during the tenure of NAE President Robert White.

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

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Volume 37, Number 3 • Fall 2007

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LINKING ENGINEERING AND SOCIETY



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## **THE NATIONAL ACADEMIES**

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# Editor's Note



George C. Maling Jr.

## Technology for a Quieter America

Noise is a problem in our society, as well as a global environmental problem, that has significant adverse effects on health and the quality of life. Today, there is a substantial gap between the present level of noise and a reasonably quiet environment—in cities, suburban communities, and workplaces. Reducing noise levels, however, raises many challenging technological and policy issues.

In January 2006, a proposal was approved and a study committee, headed by me, was appointed by NAE to investigate the economic and quality-of-life benefits that might be realized through focused efforts to reduce the negative effects of noise. The study will include a description of existing and potential solutions and recommend policies to encourage their development and deployment. Subcommittees are currently collecting, synthesizing, and analyzing information on applications of current technology, research and development initiatives for noise control technology, and intergovernmental and public-relations programs.

The articles in this issue of *The Bridge* address some aspects of these issues. In the first article, William Lang and I provide an overview of the engineering and policy challenges to reducing unwanted noise. Several of the areas we touch upon are then taken up in subsequent articles.

For American manufacturers to remain competitive in the global economy, we will need engineers trained in noise control engineering and human responses to noise. Richard Lyon and David Bowen describe the

challenges to designing and producing quieter products. Patricia Davies, a professor at Purdue University and an expert in the new field of perception-based engineering, addresses the human aspects of noise reduction and the metrics we use to measure noise. She describes interdisciplinary research on many fronts for addressing the concerns of ordinary people about noise in indoor and outdoor environments.

Transportation noise is pervasive in our world. People are subjected to noise from cars and trucks, freight and passenger trains and light-rail urban transit systems, and aircraft, especially around airports. These issues are discussed in an article by three authors, Ian Waitz, Robert Bernhard, and Carl Hanson.

Finally, Robert Bruce addresses the serious problem of excess noise in the industrial workplace, which causes hearing loss and other health problems for many workers. He describes many available engineering noise-reduction methods that could be used to change the noise environment for millions of workers. However, in many cases, reducing employees' noise exposure will require new technologies.

Many of the articles also touch on how government responses to noise issues can be improved. Although there is some cooperation among government agencies on the state and federal levels, noise programs, local ordinances, and government regulations can all be greatly improved and better coordinated.

We recognize that the challenges to noise reduction pose great difficulties from a technical and a policy standpoint. However, we also recognize that our country needs to address these issues for reasons of health, individual quality of life, and national economic competitiveness.

*George C. Maling Jr.*

*Noise can be controlled at the source, along its path, or at the location of the receiver.*

# Noise as a Technological and Policy Challenge



William W. Lang



George C. Maling Jr.

William W. Lang and  
George C. Maling Jr.

## **The Source-Path-Receiver Model**

For a systems approach to the technological issues of noise reduction, the source-path-receiver model, which has been in use for many years, can provide a helpful starting point (Bolt and Ingard, 1957). This model enables engineers to treat each part of a system separately, thus facilitating identification of the technical challenges for that part. The model is illustrated in Figure 1.

Noise can be controlled at any stage of the model—by reducing it at the source, interfering with its transmission paths, and/or changing the characteristics of the receiver. The descriptors most frequently used in a noise control system are the levels of sound emission from the source, attenuation level of noise along the path(s), and the sound-pressure level at the location of the receiver (i.e., imission). A source is usually characterized by the total acoustic power it radiates into the environment and, less frequently, by the directivity of the sound radiation. Because a wide range of acoustic powers can be radiated by sources (and sound pressures at receiver locations), a logarithmic scale is used for each descriptor.

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William W. Lang is president of the Noise Control Foundation. George C. Maling Jr. is chair of the NAE Technology for a Quieter America Project, managing editor of *Noise/News International*, and Managing Director, Emeritus, Institute of Noise Control Engineering of USA Inc. Both are NAE members.

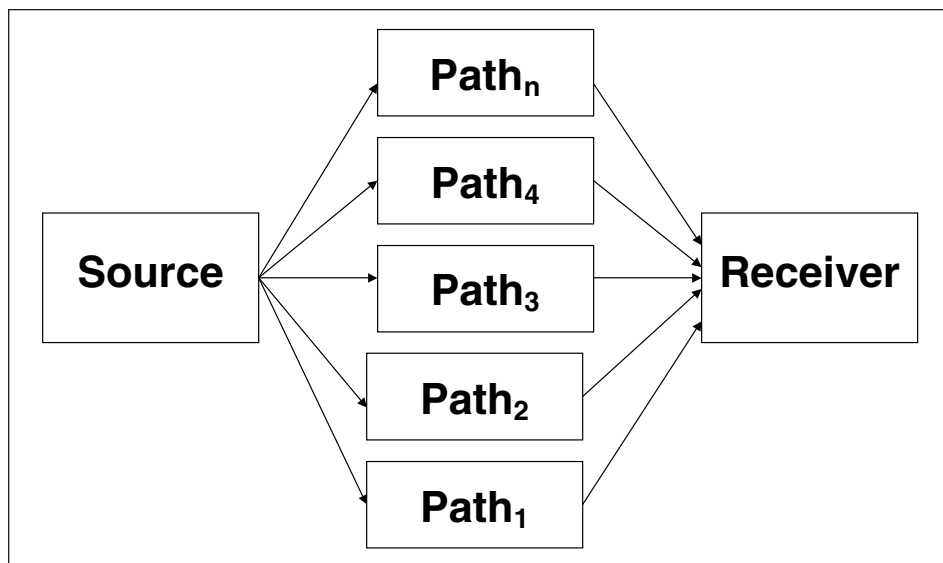


FIGURE 1 Source-path(s)-receiver model for describing noise problems.

The *sound power level*, the logarithmic ratio of the acoustic power of the source and a reference power ( $10^{-12}$  W), can be conveniently expressed in bels. The acoustic power is often A-frequency-weighted to bring the level more in line with human perception (IEC, 2002). For practical reasons, most industries prefer to use the decibel (dB) for this ratio (1 bel equals 10 dB).

An A-weighted level frequently used to describe cumulative noise exposure is the day-night sound level,  $L_{dn}$  (the time-weighted average level over a 24-hour period, but with 10 dB added for nighttime hours [10:00 p.m. to 07:00 a.m.]). The abbreviations dBA or dB(A) are often used as the unit of an A-weighted level, even though the level, and not the decibel, is A-weighted.

At the receiver’s location, the sound-pressure level, also expressed in dB, is 20 times the logarithmic ratio of the root-mean-square sound pressure and a reference pressure ( $2 \times 10^{-5}$  N/m<sup>2</sup>). Sound-pressure levels are also often A-frequency weighted.

**The Source**

The acoustic power radiated by a source is generally a very small fraction of the total electrical or mechanical power of the source. Shaw (1975) estimated this fraction to be  $10^{-5}$  with a range of  $10^{-3}$  to  $10^{-7}$  for a wide variety of sources—from dishwashers to the airplanes of that era. A more recent illustration can be derived from a current European Union (EU) Directive on noise emissions from outdoor equipment (EU, 2005). The examples below are Stage II values, which became effective on January 3, 2006.

**Example 1.** A welding and power generator with an electrical rating of 10 kW must radiate no more than 100 dB of acoustic power. The ratio of the two powers is  $10^{-6}$ . This ratio is not very different from those of a wide range of electrical ratings.

**Example 2.** A compressor with a net installed power of 15 kW must radiate no more than 97 dB of acoustic power. The ratio of the two powers is  $0.33 \times 10^{-6}$ . The ratio is smaller for net installed powers < 15kW, but not very different for powers > 15 kW.

Aerodynamic noise generated by turbulent flow or fluctuating lift forces is a common problem for aircraft, air-moving devices, and air-cooled machinery. Many sources generate aerodynamic noise, and, although once again the acoustic power radiated is a very small fraction of the power of the flow, aerodynamic noise creates significant problems in homes, offices, and communities.

Because the acoustic power radiated is small, even if the mechanical motion of a noise source is known, it is often very difficult to predict the level of sound radiation. The propagation of sound through a structure and subsequent radiation from the structure further complicate the situation.

**The Path(s)**

Theoretically, sound waves outdoors spread geometrically at a rate of 6 dB per doubling of distance. However, this seldom occurs in the real world because of sound absorption at the ground surface, ground geometry, air turbulence, and wind and temperature gradients. Although propagation models have been developed, conditions are constantly changing, and predicting noise levels at a receiver outdoors is a complex undertaking.

Silencers and mufflers are common ways of attenuating noise along a path, indoors or outdoors, and their performance can be predicted or measured. However, these devices are frequently expensive add-ons that can raise the cost of a product.

For equipment used indoors, attenuation depends on the sound-absorptive properties of room surfaces, room geometry, and the scattering of sound from objects in the room. Thus, designing machines to ensure that a given sound-pressure level reaches the receiver can be challenging indoors as well.

### *The Receiver*

Measuring sound-pressure levels, usually A-weighted, at receiver locations is a straightforward process. However, difficulties arise in correlating the physical magnitudes of the sound to the subjective and physiological reactions of the receiver. The human ear is, perhaps, the most variable receiver in its response to physical signals, because the principal effects of noise on people are both psychological and physiological.

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## *Prolonged exposure to high noise levels may have physiological effects.*

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The psychological effects of noise include annoyance, sleep disturbance, interference with communication, and adverse effects on learning, social behavior, job performance, and safety—all of which affect quality of life. However, people can adapt to many sounds. For example, they may become accustomed to sounds that were extremely disturbing when they were first heard. After hearing a sound over a long period of time, some people may find it tolerable, or even acceptable.

An example of this is someone who purchases a residential property adjacent to a busy highway. One of the motivating factors for the purchase is the reduced price of the property because of its exposure to highway noise; an equivalent property in a quiet neighborhood would be significantly more expensive. At first, the buyer may find the traffic noise annoying. But after a period of time, the negative psychological effect may fade as he or she becomes accustomed to the noise.

The ability of humans to adapt to noise, particularly when there are financial advantages in doing so, presents a major difficulty in determining metrics for community noise. It is difficult to determine physical parameters for annoyance, loudness, sleep disturbance, and other effects of noise that are subject to adaptation.

Prolonged exposure to high noise levels may have physiological effects, such as significant hearing loss caused by the atrophy of hair cells in the inner ear. Noise-induced hearing loss (NIHL) is well understood and is subject to international standardization (ISO, 1990). NIHL is frequently accompanied by tinnitus, a persistent ringing in the ears, which is sometimes severe, even for people with mild hearing impairments. Even relatively low levels of noise that are well below the threshold for causing hearing loss can have adverse effects on the auditory system—such as masking signals and alarms and interfering with speech.

Noise may also increase stress and damage the cardiovascular system. Such non-auditory effects are under investigation but have not been subject to international standardization.

### **Workplace Noise**

Excessive noise in the workplace, which has been a problem since the industrial revolution, remains a problem despite years of effort. In a study of noise and military service in 2005, the Institute of Medicine provided an assessment of costs to the federal government for compensation for hearing loss incurred during military service. “At the end of 2004, the monthly compensation payments to veterans with hearing loss as their major form of disability represented an annualized cost of some \$660 million . . . [W]ith tinnitus as the major disability . . . [the cost is] close to \$190 million on an annualized basis” (IOM, 2005). Corresponding costs for civilian federal employees in 2001 were reported by the U.S. Army Center for Health Promotion and Preventive Medicine to be about \$43.8 million (CHPPM, 2003). Thus the total cost for compensation to veterans and other federal employees is almost \$1 billion per year. Similar figures for non-federal employees in American industry are not available.

The technological challenges to controlling noise in the workplace include (1) using available technology to solve as many of the problems of excessive noise as possible and (2) developing new technology for addressing the remaining problems. According to Bruce and Wood (2003), “The lack of clear direction at the national level is the reason this very solvable problem remains a challenge to our society . . . we lack the will to resolve this problem.”

### **Highway Noise**

The principal tactic for reducing surface-transportation noise is the noise barrier, a palliative measure that does

nothing to reduce the level of noise radiated by vehicles in motion (i.e., the sources). The Federal Highway Administration (FHWA) has reported that, by the end of 2004, more than 3,500 km of noise barriers had been constructed by 45 state departments of transportation and the Commonwealth of Puerto Rico at a cost of more than \$2.6 billion (\$3.4 billion in 2004 dollars) (FHWA, 2006). Some roads have barriers on both sides, others on only one side.

The cost per square meter of a noise barrier depends on its height, construction materials, and terrain (Polcak, 2003). However, the effectiveness of roadside noise barriers is marginal. They provide a modest degree of shielding from traffic noise for residences immediately behind the barrier, but their effectiveness diminishes rapidly with distance from the barrier (Daigle, 1999).

At the present time, a low level of interior noise, particularly in a passenger vehicle, is an important sales feature. Thus market forces are driving the automotive industry to invest large sums in research and development to reduce interior vehicle noise.

No comparable efforts are being made to reduce exterior vehicle noise. At highway speeds, most exterior noise is produced by the interaction between tires and the road surface. Table 1 shows crossover speeds—the speeds at which road/tire interaction noise is equal to the power train noise—for different types and vintages of vehicles. At higher speeds, tire/road-surface interaction noise dominates.

A body of evidence now indicates that significant noise reductions can be achieved by reducing tire/road-surface noise (Donavan, 2005). The technological challenge is to engineer road surfaces and tires to reduce noise levels.

**TABLE 1 Crossover Speeds for Various Types of Vehicles**

Vehicle Type	Cruising	Accelerating
Cars produced from 1985 to 1995	30–35 km/h	45–50 km/h
Cars produced since 1996	15–25 km/h	30–45 km/h
Heavy vehicles produced from 1985 to 1995	40–50 km/h	50–55 km/h
Heavy vehicles produced since 1996	30–35 km/h	45–50 km/h

Source: Adapted from Sandberg and Ejsmont, 2002.

**Aircraft Noise**

In the 1960s, high-bypass-ratio jet engines were introduced that made passenger aircraft much quieter than their predecessors. As a result, noise generated by passenger jets sitting or taxiing on the ground and during landing, takeoff, and cruising was reduced significantly. However, aircraft operations have also increased considerably since 1960. Thus, although individual aircraft have become quieter, as required by the International Civil Aviation Organization, noise levels surrounding airports have not dropped commensurately. In a circular published by the Transportation Research Board in 2006 and in a National Research Council (NRC) report in 2002, aviation noise was still identified as a critical environmental issue.

To provide relief for residents in communities near airports, the Federal Aviation Administration (FAA) has been funding upgraded sound insulation in homes, which significantly reduces noise inside residences. The Residential Sound Insulation Program is supported by the FAA under the Airport Improvement Program and by local contributions. Near O’Hare Airport alone, 6,179 homes had been insulated by the end of 2006 at a cost of \$189 million. An additional 770 homes near O’Hare will be insulated, at a total cost of \$21.6 million. The sound-insulation program improves the quality of life inside residences but does nothing to reduce outdoor noise. Once again the problem is being approached reactively, at the path stage rather than the source stage.

The engineering challenge for the future is to develop new technologies for quieter aircraft. Major steps in this direction are being taken (NASA, 2007), but, given the lead time for new designs and the phase-out time for current aircraft, many years will pass before these efforts lead to significant reductions in airport noise.

**Noise in Urban Areas**

Noise in urban areas continues to be a problem. A hotline installed several years ago in New York City for complaints about noise logged more than 335,000 complaints from July 2004 to June 2005 (Bronzaft, personal communication).<sup>1</sup> Many complaints were about noise generated by people, for which there are probably no engineering solutions. But in a 2004 report that ranked complaints by type, several that

<sup>1</sup> Arline L. Bronzaft is Professor Emerita at Lehman College, City University of New York, and a member of the Council on the Environment of New York.

did have engineering solutions ranked high on the list—highway or street traffic, motorcycles, garbage and delivery trucks, and airplanes and helicopters (Bronzaft and Van Ryzin, 2004).

The control of noise in urban areas is regulated by building codes and local ordinances. Shoddy construction practices made possible by lenient building codes can facilitate the transmission of noise in buildings, and local ordinances may not prevent unnecessary noise from everyday activities. Enforcing noise codes can be difficult if authorities have not been properly trained or do not have the necessary equipment to make physical measurements or if the judicial system does not provide sufficient support for enforcement authorities.

In addition, requirements related to noise may differ greatly from one administrative area to the next. This lack of uniformity presents problems that must be addressed on a regional or, perhaps, national basis. A new noise ordinance for New York City that became effective on July 1, 2007, might very well serve as a model for noise control in other major urban areas (NYC, 2007).

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*U.S. companies face  
competition from foreign  
manufacturers that produce  
quieter products.*

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One serious adverse effect of excessive noise is interference with the education of children. Noise may enter the classroom from outside or inside (e.g., from air conditioners and other equipment). A summary of noise issues related to hearing-impaired children published in the *Federal Register* in 1998 (FR, 1998) led to American National Standard S12.60 on acoustical conditions in classrooms (ANSI, 2002). This problem has also been addressed in an NRC report, *Review and Assessment of the Health and Productivity Benefits of Green Schools: An Interim Report* (NRC, 2006).

The challenge for engineers is to provide technological guidance to officials and legislators who are drafting codes, guidelines, standards, and ordinances for controlling noise levels in homes and public buildings.

### **Product Noise and U.S. Competitiveness**

In recent years, the demand for quieter products has increased significantly, particularly in parts of the world to which the United States exports consumer goods and industrial equipment. U.S. companies are facing growing competition from foreign manufacturers that produce goods with lower noise levels. In many countries in Europe and Asia, people purchasing white goods are provided with information on noise levels.

For U.S. products to compete in those markets, they must be designed to meet the criteria of overseas buyers. Exported, low-noise products are becoming increasingly important to our economic future. At present, no international agreement on a labeling system has been negotiated to provide noise-level information to consumers, but U.S. companies would be wise to label their products in ways that can be easily understood by consumers abroad.

U.S. producers also face regulatory challenges, particularly in the EU where noise-emission requirements have been adopted for many products used outdoors (EU, 2005). American manufacturers must now meet these requirements for their equipment to be sold in the EU. In addition, noise-emission requirements in manufacturing facilities are more stringent in the EU than in the United States (EU, 2003). Thus a piece of equipment that can be installed in an American facility may not be acceptable for a facility in the EU.

The challenge for engineers is to assist U.S. manufacturers in acquiring the technical expertise to ensure that U.S. products are designed to meet low-noise requirements in overseas markets.

### **Educational Challenges**

Courses in noise control engineering are being taught in about a dozen U.S. universities. However, there are some indications that the demand for trained professionals in the field exceeds the supply and that industry and government are hiring people in other fields, such as aerodynamicists, crash-worthiness engineers, physicists, mechanical engineers, vibration specialists, electrical engineers, and others, to perform noise control engineering work (Bernhard, 2005). Many educators argue that engineers need graduate training and a degree in the field to be fully effective.

The challenge today is to ensure that the U.S. educational system continues to produce well trained engineers with leadership skills in the development of new technologies necessary for a quieter world.

## Noise Policy

The United States does not have a cohesive, coordinated policy for controlling noise. Nor does any federal agency have oversight responsibility. With the exception of aircraft and some aspects of railway noise, product-emission regulations are not enforced for major sources of noise. Current federal, state, and local policies are largely uncoordinated and often obsolete, and enforcement of noise regulations is uneven at best.

Meanwhile, government authorities outside the United States, particularly in the EU, are moving rapidly to protect their own interests by adopting national and international noise control policies (Beranek and Lang, 2003). The challenge to the United States is to develop an effective national noise control policy that covers products from conception to implementation.

## Political Challenges

Up to now, practicing engineers and others with backgrounds in engineering have played a limited role in the development of noise control policies in the United States, even though they have the best understanding of the technological challenges involved. The challenge for engineers is to play a decisive role in the future.

As Senator John H. Sununu, an NAE member, warned almost two decades ago (Sununu, 1989):

*It is clear to engineers and scientists . . . that science and technology—engineering—not only continue to play a role in improving quality of life . . . but also are critical to developing and implementing policy at the national and international level . . . I stress this point because I am concerned that engineers in general have been negligent in their direct participation in the process of shaping and implementing public policy.*

Engineers can, and must, play an active role in defining the requirements for a national noise control policy. Engineers can clarify for legislators the challenges and limits of noise control technology. They can provide policy makers with technical knowledge of the major sources of noise, the noise emissions of competitive products in the world, the relative importance of each noise source to properly balanced noise reduction, the techniques available for reducing noise from various sources, and the research and development programs necessary to find ways to reduce noise from sources for which no satisfactory techniques have been developed (Beranek and Lang, 2003).

## Conclusions

The United States urgently needs a new national policy based on technological innovation with the emphasis on citizen/industry/government cooperation and with funding for new research projects, as needed. A national noise control policy would improve the quality of life in America. It would conserve the hearing of workers in our industries, enhance their productivity, and reduce the number of accidents. It would reduce noise in our cities and preserve quiet in our wilderness areas. Our children would benefit from a quiet classroom atmosphere that enhances their learning and social skills.

A carefully considered, coordinated policy would encourage American manufacturers to produce low-noise products and put the United States in a position to work with other nations on the development of a global noise control policy that could lead to a quieter world for people everywhere.

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*New technologies can lead to quieter mechanisms and materials or unexpected, unpleasant sounds.*

# Designing Quiet Products



Richard H. Lyon



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Sounds made by products can be either pleasing or annoying. Sounds are pleasing when expectations are met and the decision to acquire the product is reinforced (e.g., the familiar sound of a car door closing). Product sounds are annoying when they are unexpected, intrusive, or raise concerns about the function or quality of the product (e.g., a knocking sound in the engine). We tend to refer to sounds in the latter category as “product noise.”

This article describes some trends in product design and engineering that have made some products noisier and some quieter. In some cases, quieter mechanisms and materials have replaced noisier ones, but in other cases new technologies have led to unexpected and unpleasant sounds. Psychometric methods that correlate design alternatives and user perceptions are helpful in designing products with sounds that are pleasing to consumers.

## Definition of “Quiet”

These days, most product managers understand that the descriptor “quiet” has a broader meaning than “less loud” as measured on a sound-level meter. The sound made by a product must be appropriate to the nature and use of that product, and even small sounds that are inappropriate or distracting should be

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avoided if possible. Designers also realize, however, that appearance, performance, and functionality are also (maybe even more) important than “quietness” to customer satisfaction. Designers must balance the latter attributes, which they understand very well, with the product sound, which is harder to nail down. Unfortunately, some current design trends that work toward satisfying other requirements make designing “quiet” products more difficult.

Quantifying the correspondences between design choices (e.g., materials, geometry, mechanisms, parts layout, and assembly sequence) and the perceptual reactions of people to the sound of that product can seem like an insurmountable task. The complexity of sound-generation processes and the inherent variability in people’s perceptions to those sounds creates much “scatter” in predicting user reactions. Nevertheless, through careful experimental design and testing, consistent relationships between design choices and perceptions of acceptability (so-called product sound quality) can be established.

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## *Trends in the development of electric motors have led to noisier products.*

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### **Trends That Make Products Noisier**

Fifty years ago, an absorption refrigerator was absolutely silent except for the hiss of a small gas flame. Some years later, the hermetically sealed compressor in an electric refrigerator was fairly unobtrusive, although not silent. However, the condenser coils on the back of the refrigerator and the 2 to 3 inches of wall thickness required to accommodate thermal insulation reduced the interior space of the refrigerator; therefore, the condenser coils were moved to the base of the refrigerator, and the wall thickness was reduced to less than 2 inches. As a result, the compressor had to work more often to counteract heat conduction through the walls. In addition, heater coils were placed in the walls of some refrigerators to reduce sweating in humid weather. Refrigerators, which once had no fans, now have two—one for the condenser coils<sup>1</sup> and one for the

freezer compartment. As a result, refrigerators are now much noisier than they used to be.

In addition, customer demand for lighter weight, more color options, and interesting shapes and configurations has led to housings for many products made of rigid, low-density plastics. Because these housings are light weight, it is more difficult to isolate them from the forces of the motors and air-handling devices, and, because of their reduced mass, they vibrate more.

Another reason for more product noise is that sound can escape more easily through stiff, lightweight walls. At the same time, the resonance frequencies of the structural modes of the housing increase as the result of the combination of stiffness and reduced mass, thus increasing the radiation efficiency of the structure and moving the sound frequencies into the “loudness and annoyance” range.

Trends in the development of electric motors have also led to noisier products. Induction, universal, and DC-commutator designs are being supplanted by, for example, variable frequency induction, brushless DC, and hysteresis motors, all of which convert a supply voltage to DC, then convert the DC voltage to an AC voltage (single or multiple phase) to control speed and torque, which makes the motor more programmable and can improve energy efficiency and increase performance flexibility. Generally, the AC voltage produced is far from sinusoidal, leading to vibrations at frequencies well above the basic excitation level. Although these small vibrations may not affect the operation of the motor, they do produce audible noise that may be objectionable.

Hysteresis motors are attractive for some applications because of their high starting torque, but this can be accompanied by fluctuating forces that produce vibrations that radiate sound. The forces between rotor and stator can be computed fairly accurately, but the generation of vibrations and the transmission of those vibrations to surfaces that radiate sound can be very difficult to predict.

Even in conventional motors, design trends have increased noise. To improve performance and reduce the size of the overall package, the power density in motors has increased. Current designs for universal motors are a fraction of the weight and size of the electric motors of 50 years ago. Some of the change is attributable to better magnetic materials, but sometimes the motor is excited to the point that the magnetic circuit is driven to saturation, which increases the harmonic content of

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<sup>1</sup> Convection cooling has been tried but does not work well with the new placement of condenser coils.

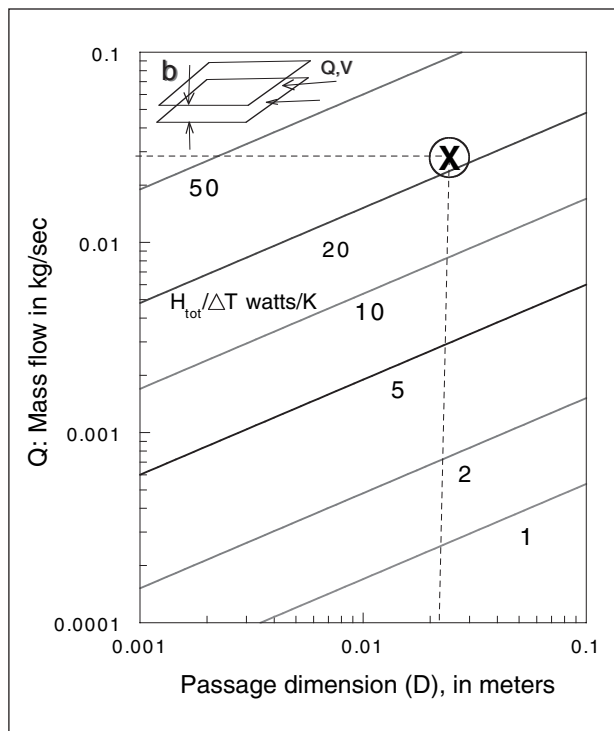


FIGURE 1 The heat transfer for airflow between circuit boards. The location X indicates the operating point of a particular design.  $Q$  = mass flow rate (in kg/sec);  $V$  = air velocity (in m/sec);  $H$  = heat flow rate (in jwatts);  $\Delta T$  = temperature difference, parts to air (in K);  $b$  = plate to plate spacing (in m);  $D = 2b$ . Source: Lyon and Bergles, 2006. Reprinted with permission of IEEE.

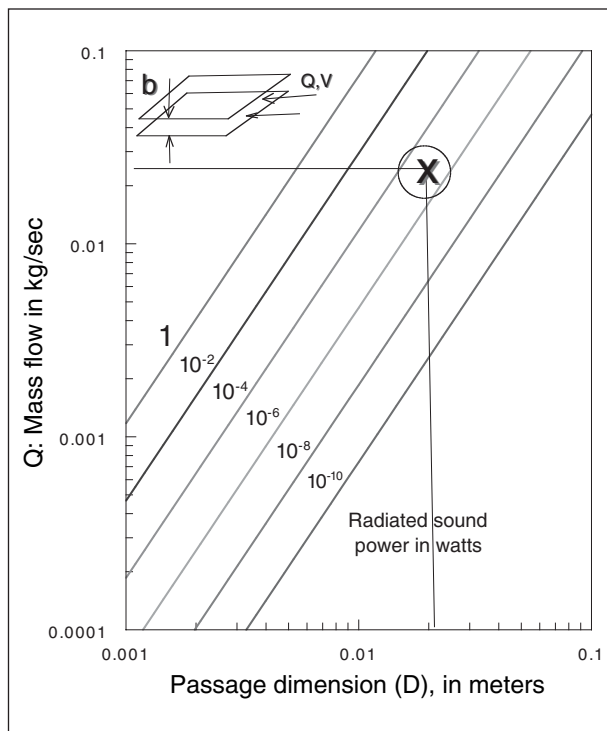


FIGURE 2 Sound generated by the flow of cooling air between circuit boards at the operating point shown in Figure 1.  $Q$  = mass flow rate (in kg/sec);  $V$  = air velocity (in m/sec);  $b$  = plate to plate spacing (in m);  $D = 2b$ . Source: Lyon and Bergles, 2006. Reprinted with permission of IEEE.

the excitation and causes the magnetic field to balloon around the motor and attract nearby ferrous material. Garage door lift motors, for example, attract the sheet-metal steel frames that support them and produce this kind of product noise.

Another less obvious cause of increased product noise is changes in manufacturing and assembly methods. “Design for manufacture” is a popular theme, but when parts are assembled by a sequence of layering operations, assemblies may have tolerance stack-up problems that lead to more noise (and other problems as well). For example, a popular food-preparation appliance was beset with such problems when new assembly procedures were introduced. Because of the lay-up of shafts and gears in the drive system, the motor could not maintain a constant speed ratio, which led to excessive gear noise (so-called “transmission error”).

**Irreducible Noise**

Electrical and electronic equipment is cooled by passing air over the elements. This airflow is normally turbulent for higher cooling efficiency, and correlations

have been developed between airflow parameters (e.g., velocity, turbulence length scales, temperature rise) and passage parameters (e.g., geometry, dimensions, heat release). Balancing heat transport with acceptable temperature rise and pressure drop is a design issue for laptop computers and digital projectors, which are being produced in smaller and smaller packages with the same, or even higher, performance levels.

Turbulent heat transfer inevitably creates a certain amount of noise, which we can label irreducible, because heat-transfer processes and noise generation by turbulent airflow in restricted passages are inextricably linked. As the air flows, the turbulent eddies decay and new ones are created, which produces forces on the components that generate sound and, at the same time, carry heat away from the surface. Thus noise generation is inevitable with turbulent heat transfer. Figures 1 and 2 show the calculation of heat transfer to sound for airflow between banks of circuit boards.

Another aspect of airflow is the pressure drop (or head loss) in the passages, which must be overcome by fan(s). Figure 3 shows the additional sound produced

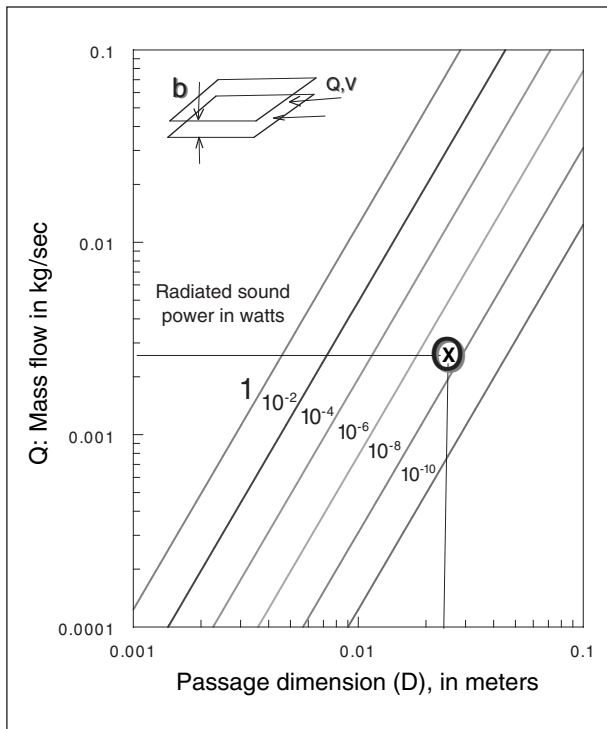


FIGURE 3 Sound generated by a well designed fan that would provide the airflow required in Figure 1. The location X indicates the operating point of a particular design.  $V$  = air velocity (in m/sec);  $b$  = plate to plate spacing (in m);  $Q$  = mass flow rate (in kg/sec);  $D=2b$ . Source: Lyon and Bergles, 2006. Reprinted with permission of IEEE.

by a well designed fan that provides airflow power to overcome this loss. Keep in mind that the actual noise produced by a fan depends on the inlet and outlet flow patterns and the aerodynamics of the blades. A poorly designed fan may produce significantly more noise than is predicted in this figure.

A good part of the noise from rotary lawnmowers arises from airflow around the cutting blades, which are designed to lift the grass by the flow they induce and then cut by impacting the grass at high speed, before it can “get out of the way.”<sup>2</sup> The airflow around the cutting blades radiates sound according to a dipole model of sound generation; airflow noise from grass-cutting blades increases as  $V^6$ . This means that a 10 dB reduction in noise requires a 17 percent reduction in speed and a 32 percent reduction in the impact force between the cutting blade and the grass. If noise reduction were achieved by slowing the blades, the mower would no longer cut grass!

<sup>2</sup> In the European Union, a directive was circulated requiring significant reductions in noise produced by lawnmowers used on golf courses and in parks.

## New Technologies

One way to make products quieter is to change the technology. For example, printers are quieter because impacting print heads have been replaced by laser beams and ink-jet drops. Hard disk drives are quieter in some products because they have been replaced by solid state memories. The gains were offset a bit because sound made by keyboards had to be increased to provide feedback for the user.

Examples from digital technology are easy to find, but there are also examples in other types of products. The takeoff noise of jet aircraft has been greatly reduced by the advent of high-bypass-ratio jet engines, which increase the scale of turbulence and decrease the speed of the ejected air for a given amount of thrust. The acoustical benefit was not the goal of these changes, however. The goal was to increase fuel efficiency and lower speed thrust, which makes the airplane more “drivable.” Less noise was a happy accidental by-product! In fact, the relationship between higher efficiency and less noise also applies, to a certain extent, to fan-related noise in general.

An example of changes in an industrial process that has reduced noise is the way nails are manufactured. Traditionally, nails were made by chopping wire to a certain length and then holding the cut piece while the head was hammered flat, a noisy procedure. The process also required that the wire be oiled and then that the oil be removed. A machine developed in the Netherlands produces nails much more quietly by replacing chopping and hammering with a rolling method that uses plastic flow of the ductile wire material. A side benefit is that the nails do not have to be oiled, and therefore, degreased at the end of the process.

As these examples show, noise may not be the driving force behind new technologies that result in quieter products. But it is also true that if a product becomes significantly noisier, resistance to using it will be greater, depending on how users and bystanders react to the noise, which brings us again to the issue of human perception.

## Good Sounds and Bad Sounds

Why does one car sound sportier or more “aggressive” than another car with a comparable engine and performance? Why do we find noise from one vacuum cleaner less annoying than from another? To answer such questions, and to incorporate the answers into the design of a product, requires product sound-quality engineering,

a discipline that has arisen in the last 30 years or so. Sound-quality engineers dissect the acoustic signature of products (either existing or virtual), compare them subjectively and objectively, and define ideal (or target) signatures for the product sound.

Because the desired sound involves peoples' reactions, achieving that sound is similar in some ways to determining the right color, surface texture, or shape for the product. For all of these characteristics, objective physical measurements only go so far toward determining the target. Unlike sound, however, the more aesthetic aspects (e.g., color, texture, etc.) are generally independent of other aspects of the product design.

Sound is affected by many of the basic features of a product. The sources of motion, their interconnections, and the structures that hold them in place all contribute to sound generation. Thus the product design must connect the choices for these physical components to the perceptual reactions of consumers.

Sound may enhance or detract from the pleasure of using a product. In addition, sound may indicate how well the product is working. Procedures can be incorporated into the design process so that the positive attributes of the sound are identified and enhanced, and the negative ones are reduced. One approach combines product-sound analysis to identify the major components responsible for the overall sound with jury testing of an array of virtual designs. This procedure can provide specific design goals for the sound of a product in terms that can be specified (e.g., likelihood of purchase, perceived quality, overall acceptability, etc.) and that engineers can address (e.g., a reduction in water-splash noise in a washing machine or changes in the fan-related tonal sound in a vacuum cleaner).

Two types of consumer-oriented "sound studies" (focus-group studies and sound-quality jury tests) can be used to determine the importance of noise to the potential end user of a product, what the consumer expects of the product in terms of noise, and how much extra the consumer might be willing to pay for "improved sound quality."

#### *Focus-Group Studies*

A focus-group type of study might be conducted, in which qualified participants are asked to describe the relative importance of sound in relation to all other aspects of a product. The focus group can help identify subjective impressions conveyed by the product sounds that consumers feel are important. These perceptual

attributes may include loudness or "strength" of the sound, effectiveness of the product, perceived quality, overall acceptability of the sound, and so on.

Of these, only loudness can be reliably predicted by a physical measurement. Other so-called "sound-quality metrics" that have been developed for an attribute of a single product (e.g., jet aircraft), or sometimes for no specific product, use simple sound stimuli, such as tones, clicks, and bands of noise, designed not to convey connotative meaning. However, meaning cannot be avoided when psychoacoustics are applied to product sounds.<sup>3</sup>

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## *Sound may enhance or detract from the pleasure of using a product.*

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#### *Sound-Quality Jury Testing*

A sound-quality jury test is another method of determining the relationships between possible design changes in a product and consumer responses. The goal of these tests is to quantify consumers' sensitivity to changes in the sounds of specific components and mechanisms in a product, in the context of overall product sound. Ratings for different combinations of attributes are used to determine which modifications optimize "sound quality." For example, even though tones and transient clicks or modulations may not significantly affect the sound level or loudness of a product, they can be audible and thus important in the overall "acceptability" of a product (Cann and Lyon, 1997).

Sound-quality jury studies can be conducted in two ways. First, a jury of consumers/users is presented with the sounds of various "virtual" products based on quantifiable variations in the sounds of the major noise sources in the product; the variations are made using a statistical design-of-experiments approach. After regression analysis of the jury ratings, a numerical relationship is established between a user perception,

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<sup>3</sup> The focus of psychoacoustics has been on how the auditory system assembles and processes acoustic information, peripherally and centrally. Therefore, traditional psychoacoustic methods do not provide guidance for predicting listener responses to the complex, actual sounds of products.

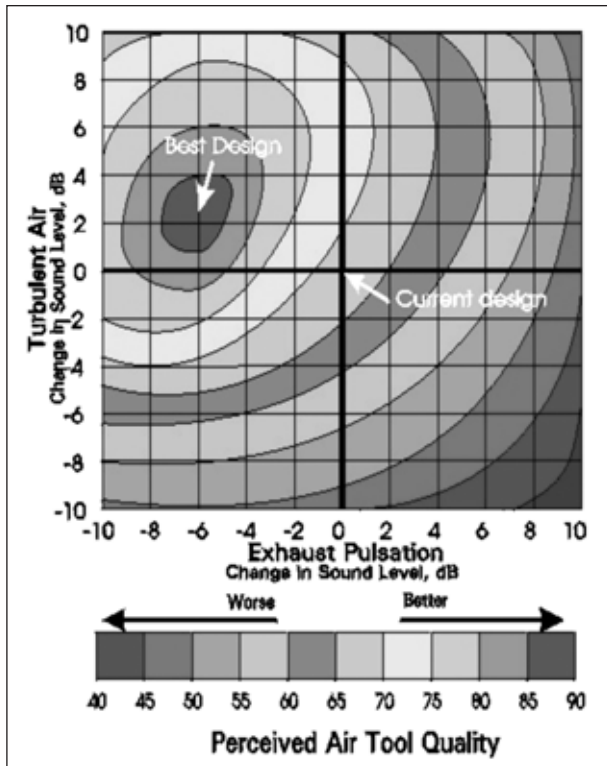


FIGURE 4 Response surface for perceived quality as a function of change in sound levels for two of the noise sources in an air-powered tool. The levels are based on sound-quality jury testing.

such as acceptability of the sound or the likelihood of purchasing the product, and changes in the sounds of the noise-producing components. Figure 4 shows an example of a “response surface” for an air-powered tool. This kind of result indicates different ways of achieving similar levels of improvement in sound quality rather than indicating how to achieve the absolute maximum sound-quality rating.

The second type of jury study involves presenting the sounds of a few products with different degrees of “sound treatment,” using an appropriately designed statistical approach. The sounds are either recorded directly from actual products (perhaps competing brands) with different sound treatments or simulate different treatment levels based on recordings made from a standard product (including a few candidate designs based on the first type of jury study, described above). The end result of the second type of jury study is a preference ranking of the sounds (e.g., products).

Once jury ratings have been determined for a type of product, it is often possible to establish a correlation between the ratings and a combination of standard or customized sound-quality metrics, with the aide of

statistical methods (e.g., principal components or factor analysis). As long as the product type remains the same, there is no need to reconvene a jury for analyzing the effect of subsequent product modifications.

### New Tools

Product design in general has been greatly affected by new computational tools, such as computer-aided design (CAD), computer-aided manufacturing (CAM), and finite-element analysis (FEA). Product-noise analysts and designers also use FEA and other software, such as boundary-element analysis (BEA) and statistical energy analysis (SEA), in addition to a host of software packages, for processing and analyzing experimental data on product prototypes.

With CAD tools, the shape and structure of a product can be designed, and the forces and motions generated by the mechanisms can be analyzed. FEA can then be used to calculate the resulting vibration, flow patterns, and temperature distributions in the product. BEA tools can then be used to calculate the sound radiated from structural vibrations.

Although CAD and FEA work well for analyzing appearance, ergonomics, fluid flow, and temperature, they are less helpful for predicting product sound for a variety of reasons. Take damping, for example, an important parameter in predicting vibration and sound levels that is notoriously difficult to predict. Damping is almost always introduced as a known parameter. Sound radiation is sometimes determined primarily by the dynamic conditions at the edges of structures where FEA may be least reliable.

For these reasons, canonical models (e.g., sound radiation by flat plates or cylinders) and semi-empirical tools (e.g., SEA) have been useful. Although they lack the apparent precision of FEA and BEA methods, they retain parameter dependence in their formulations, and they can predict trends in sound levels as those parameters change.

### Self-Image, Demographics, and Economics

People regard some products as utilitarian commodities (e.g., air conditioners, air compressors, paint sprayers, and electric can openers) that have little if any associations with self-image. Other products, such as automobiles, golf clubs, and cameras, have potentially more associations with self-image. For many years, white goods (e.g., refrigerators, dishwashers, clothes washers, and dryers) have been treated as

commodities that are purchased primarily on the basis of price and function.

In the last 50 years, the price of an automobile has increased by a factor of 20 to 25, from about \$1,500 to \$30,000 to \$40,000. In the same period, the price of a dishwasher increased by a factor of about 5, from \$150 to \$750. This has made it much more difficult for manufacturers of white goods to absorb the costs of improvements, particularly in the area of product sound. Indeed, the need for cost reductions in materials and components in white goods has made it difficult to keep product noise from increasing.

For some time, European white goods (a misnomer because many European products have brushed-steel exteriors) have been quieter than comparable U.S. products, but the prices of European products are generally much higher than for their U.S. counterparts. European products are quieter because of heavier construction (stainless steel instead of plastic tubs), more sound-absorbing materials, and better isolation of vibrations from motors, pumps, and water piping.

Recently, however, kitchens themselves, as well as kitchen equipment, have become a matter of pride for many U.S. families. As a result, they are purchasing many more high-end products, which are quieter, not because of breakthroughs in noise-control technology, but because of well-known acoustical principles. These

products are available because of marketplace demand and the willingness of consumers to pay higher prices for them.

## Conclusion

For the foreseeable future, designing quiet products is likely to remain a combination of analysis, experimentation, and the application of well-known principles in sound and vibration. Product-design teams must include engineers with expertise in computational methods as well as in acoustical technology. But the idea that a designer will draw a CAD model, analyze the product for vibration with FEA, compute the sound radiation with BEA, and then build a prototype with the predicted product sound that has been declared favorable by a psychometric model is a pipe dream, because every one of these tools has deficiencies in areas that are critical for acoustical behavior.

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*Product-design engineers should be educated in measuring and analyzing how people perceive noise.*

# Perception-Based Engineering: Integrating Human Responses into Product and System Design



Patricia Davies is a professor of mechanical engineering at Purdue University and director of the Ray W. Herrick Laboratories, an institution dedicated to graduate education and engineering research, including noise-control engineering.

Patricia Davies

**E**ngineered systems produce both wanted and unwanted products. For example, a computer printer produces text and images but also produces noise in the process. Yet, in the printer-design process, people's perceptions of the quality of the noise and the quality of the images are often left out of the definition of what constitutes a good printer. In the past, designers have striven to design printers that produced exact replications of original images. In fact, it would be more effective to focus on replicating the characteristics of the image that are important to the observer (Wu et al., 2001).

Once the imaging problem has been solved, designers must address the noise problem. Merely reducing the level of noise may not be sufficient, because even soft sounds may be annoying if they fluctuate (changing sounds tend to attract attention). However, people might like to hear that the printer is operating, so eliminating noise altogether is not desirable either. The sound must meet people's expectations.

In general, noise control should be focused on reducing the sound attributes that are most annoying or that cause acoustical discomfort and enhancing the sound attributes that people wish to hear. This can be difficult, however, if several outputs or different audiences compete rather than complement each other. In the case of the printer, for example, increased speed may mean increased noise and lower print quality. Or desirable sound for the person awaiting the printed page may be annoying or worse

to the person working close to the printer. How should designers make these trade-offs?

**People-Sensitive Criteria**

Clearly, “people-sensitive” criteria must be included in the design process. However, the development of these criteria is problematic for most designers, because they are rarely educated in measuring and analyzing how people perceive the outputs of their products. Thus, if end users’ opinions are considered, they are usually tested with ad hoc methodologies developed without the help of psychologists, who are trained in making these types of measurements. In addition, testing is usually done so late in the design process that significant changes are no longer feasible. Whereas an integrated design approach might not lead to higher cost, add-on solutions at the end of the process always increase cost.

**Perception-Based Engineering**

Perception-based engineering is a term coined by professors at Purdue who were working on a proposal

that involved a number of existing, collaborative research projects between engineering and psychology, such as automatic speech recognition, control of machine noise, automotive interior design, air quality, touch interfaces, printer design, and highway design. Although at first glance these projects may not have much in common, all of them were focused on getting a better understanding of how people perceive, process, and make decisions in response to intended or unintended stimuli—usually generated by machines or engineered systems. For example, the text and images produced by a printer are intended outputs whereas noise is an unintended output.

In perception-based research, engineers and psychologists work together to develop models of human information processing and decision making. By connecting engineering stimulus-prediction models to perception models and decision-making models, design options can be explored, compared, and optimized to reduce negative impacts and accentuate positive impacts.

Figure 1 is a sample of this model-building process from a study of how combustion variability impacts the

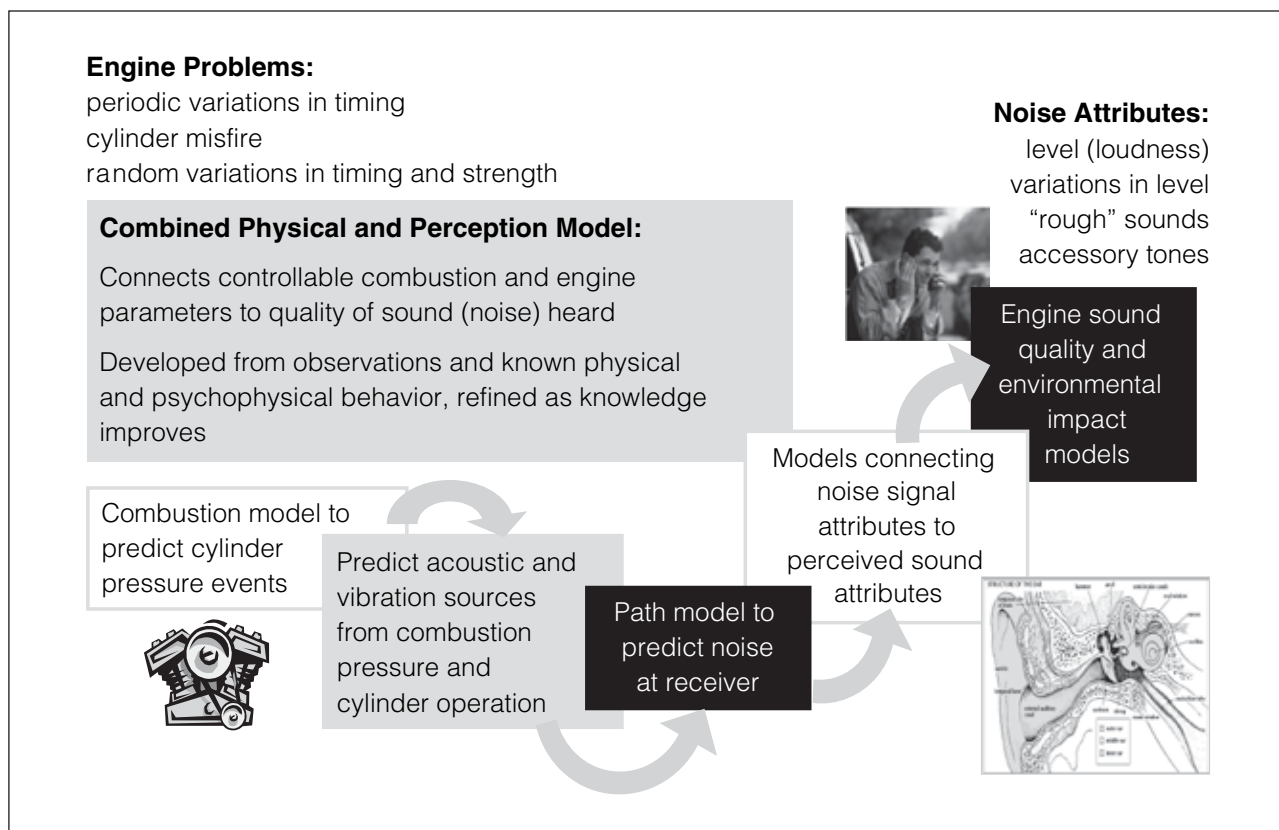


Figure 1 Illustration of a model, in this case combining perceptual and engineering models for a study of diesel-engine sound quality. Source for human ear graphic: <http://bmrh.boystown.org/cel.ear.jpg>.

sound quality of diesel engines (Hastings, 2004). Chen and Chiu (2004) used a similar model to address the perception of color banding in printed images (stripes that appear in the image in the print direction). Their goal was to design a printer-control algorithm to compensate for imperfections in printer components, thus removing perceptible banding in the printed images.

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## *Engineers do not always use appropriate metrics to quantify human responses.*

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An understanding of effective human information processing can be extremely helpful in the development of “perceptive” machines—for example, word-recognition machines focused on the automatic detection of nouns and names (Surprenant et al., 1999); studies of multi-modal gestures and speech (Harper and Shriberg, 2004); and haptics research being used to develop tactile displays of speech for people with hearing and visual impairments (Israr et al., 2006).

The overall purpose of perception-based engineering research is to integrate the ways people perceive, and are affected by, machinery outputs into the design of engineered systems:

- to understand how machine outputs (intended and unintended) impact people (e.g., comfort, annoyance, task performance and productivity, perception of product quality, etc.) as a basis for developing people-sensitive metrics for product design
- to understand how people process information (tactile, acoustical, visual, etc.) and use this understanding to emulate efficient human information processing to enhance machine performance
- to understand human-machine interactions to develop safer, more efficient, more user-friendly interfaces

Perception-based engineering is a component of human-factors research, but the emphasis is on the integration of human-response models into engineering product design rather than on the more traditional interface design, ergonomics, and human performance (Proctor and Van Zant, 1994; Salvendy, 2006). However, the dividing lines are permeable. Human-factors

researchers at Purdue are active participants in perception-based research, and performance and productivity, as well as perception and comfort, should all be taken into account in engineering designs.

### **Metrics for Quantifying Human Responses**

Although incorporating human response into product design may seem like common sense, it is often omitted, particularly for products with which users have little direct interaction. Even in products where attention is paid to the user-interface design, human response to unintended stimuli (e.g., noise, heat, vibration, etc.), which directly affect the surrounding environment, is often ignored. When engineers do consider human responses, they do not always use good metrics to quantify them.

Statistics based on A-weighted sound-pressure levels are widely used, even when this weighting is inappropriate because of the very high level of sound. A-weighting should only be applied to relatively quiet sounds (40 dB or less). As a reference, 40 dB(A) is approximately the quietest level of background noise in a city during the day (Beranek, 2005). Humans are more insensitive to lower frequency sounds and very high frequency sounds than to sounds at frequencies in between; but this relative insensitivity is more pronounced for quieter sounds. Thus when A-weighting is used on high-level sounds, low-frequency components are attenuated more than they should be. In spite of this, A-weighting is very commonly used for sound-pressure levels above 40 dB.<sup>1</sup>

Another inappropriate criterion is the sum of squares of error (i.e., pixel differences between ideal images and reproduced images) in the evaluation of image quality. If perfection were possible, this might work, but, because there is always some imperfection, using this type of metric does not necessarily lead to better quality images (e.g., a lower error score may produce a poorer image). A different type of metric, such as the image-fidelity assessor developed by Wu et al. (2001), which is based on an understanding of what people look at in images, is a better way to determine where in the image more detailed image processing would make a difference.

### **Modeling Human Responses**

If the modeling of human responses is included in engineering design curricula at all, it is usually in a

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<sup>1</sup> In the early days, there was A-, B-, and C-weighting. B-weighting is rarely used today. C-weighting—which is basically flat-frequency weighting—is still used for some sounds.

superficial way. I often get the impression from my engineering colleagues that they do not think human response can be modeled. Even though we all observe people responding in similar ways to similar inputs, when engineers are challenged to incorporate human-response models into the design process, they tend to focus on the variability of people's responses rather than data that might explain common response characteristics. Because they do not understand the influence of context and individual experiences on the response, they conclude that people's reactions are "random," and there is no point in modeling them. (Human-factors engineers are an exception, of course, but they are not involved in the design of most machines and engineered systems.)

In contrast, engineers gladly accept the challenge of modeling highly complex engineering systems, even when they are not certain of the exact mechanisms responsible for the observed behavior. In this context, they are comfortable with the concepts of approximation and variability, and they may develop strategies for reducing the influence of noise based on estimates of parameters from experimental data, account for un-modeled dynamics and environmental conditions, develop experimental strategies to improve their understanding of the mechanisms at play, and incorporate statistical properties into their models. They rarely feel that these significant uncertainties prevent them from building models.

### **Psychophysical Techniques**

An interesting aspect of the work of my colleagues in quantitative and cognitive psychology is psychophysics and the methodologies used to control and understand biases. From them, I have learned that great care must be taken in designing and executing experiments to prevent uncontrolled biases or confounding variables from obscuring the behavior of interest or its causes. When engineers and psychologists collaborate in their research and learn more about the complexities of human-response testing, engineering students often come away with great respect for their counterparts in psychology.

Although engineering measurements seem straightforward by comparison, in some sense, all test engineers grapple with similar problems (e.g., (un)controllable environments, system memory, external inputs [noise], repeatability, etc.). There are also similarities in the model-building and data-analysis methods used in both

fields. For example, an analysis technique used to identify the number of independent sound sources generated by a machine is essentially the same as the technique used to identify the independent sound characteristics people hear when listening to a given set of sounds. This should not be surprising, because both are focused on understanding the underlying structure in the data.

### **The Acoustics Community**

The acoustics community spans many disciplines—physics, music, engineering, human and animal physiology, medicine, sociology, and psychology, and acoustics conferences, which usually attract people from many different fields, can facilitate interdisciplinary interactions. Nevertheless, there often is very little dialogue between groups working on similar problems from different perspectives, even within the acoustics community. And dialogue does not always lead to an integrative approach to solving problems.

For example, research in psychoacoustics on how people judge the loudness of a sound is producing a wealth of knowledge. Models have been developed that incorporate many of the complex frequency and temporal attributes of the human hearing system, and it is now possible to predict the loudness of most sounds very accurately, even sounds that vary in time (Glasberg and Moore, 2002; Zwicker and Fastl, 1998). Reasonably good models have also been developed of how people judge other attributes of sound (e.g., sharpness, roughness, fluctuation, tonality). However, the understanding of sound perception and the corresponding models have not propagated to other parts of the acoustics community.

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*Research in psychoacoustics  
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knowledge about how  
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The distance of the design engineer from the people who experience the product outputs, including noise, is one problem. Goals set locally may not address the needs of the recipient of the product sound, which, if unwanted, is perceived as noise. An engineering

designer working on noise control in aircraft engines, for example, is probably using a standardized metric developed decades ago that does not incorporate advances in our understanding of how people perceive sound. Thus the designer probably does a good job of reducing the metric value to “improve” the sound. The question is whether he or she is using the correct metric.

In this example, the chain of engine-aircraft-airline-passenger or community resident isolates engine-noise engineers, who have a profound influence on the comfort of passengers and community residents. When noise-control engineers make choices between different designs, they don’t always understand the implications of those choices.

### **Quieter Isn’t Always Better**

It has been known for a long time that an A-weighted sound-pressure level can be decreased without making the sound quieter. Sometimes when loudness is reduced, sound components that were previously masked become audible, thus making the sound more prominent, or even seemingly louder (Hellman and Zwicker, 1987).

If these are high-frequency, time-varying, and/or tonal (discernible pitch) sounds, the overall result might be a less desirable sound. For example, reducing fan noise in refrigerators to reduce A-weighted sound pressure may make compressor noise (which is often time-varying, tonal, high-frequency noise) more prominent. Thus the resulting sound may be more annoying than the original sound (May et al., 1996).

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*An A-weighted sound-pressure level can be reduced without making the sound quieter.*

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The automotive industry uses sound-perception and acoustical-engineering models to produce better sounding products (Lyon, 2003). A group of automotive engineers has developed guidelines to help other engineers develop sound-perception and preference models (Otto et al., 2001). Recently, noise-control engineers in other industries have shown more interest in the concepts of sound quality and product-sound

design, especially because some noise characteristics can not be measured by the acoustic metrics they have been using.

Engineers are beginning to realize that if a product sounds good, people may think the product is good—and those people may be right! Noise is often a symptom of problems, and changing the sound by changing the design often leads to improving the product in other ways, such as making it more reliable, more energy efficient, and so on.

The product-sound community is slowly adopting a more psychoacoustics-based approach to noise measurement and taking the time to develop an understanding of what people hear and pay attention to in making decisions about products. Some sound engineers are even adopting sound-perception models.

### **Community Noise**

In contrast, the measurement approaches used to assess community noise have changed very little for a number of decades. Although there have been some discussions about the structure of models relating noise to other factors, such as sleep disturbance or annoyance, the sound metrics used as inputs to these models are typically based on statistics of A-weighted sound-pressure levels (e.g., sound-exposure levels [SELAs], and day-night levels [ $L_{dn}$ ]). Some researchers have advocated using loudness metrics (Schomer et al., 2001), but not metrics based on the most recent models of loudness for time-varying sounds (Glasberg and Moore, 2002; Zwicker and Fastl, 1998).

Several concerns have been raised about using A-weighted metrics to assess community noise. For example, there have been questions about using 65  $L_{dn}$  contours around airports for planning, a level which, in the transportation data collected and analyzed by Schultz (1978), relates (on average) to about 15 percent of the population finding airport noise highly annoying. Schomer (2002) points out the high level of variability in the data (90 percent of the data from surveys at 65  $L_{dn}$  falls between 5 and 28 percent of people being “highly annoyed”) and recommends that normalization methods be used to account for context and sound characteristics; this is very much in the spirit of perception-based engineering. Other issues related to A-weighted metrics are the influence of isolated noise events (to which time-averaged levels are relatively insensitive) and low-frequency noise (which has the potential to cause vibration and rattle).

The value of  $L_{dn}$  that corresponds to a particular percentage of the community being annoyed by noise is different for different transportation sources (Miedema and Vos, 1998). Thus predicting noise impacts in areas where multiple noise sources are present can be challenging. Some argue that knowledge of the noise source influences the response (e.g., people *prefer* trains to road traffic and thus find train noise less annoying than road noise, even at the same noise level).

Others argue that the differences only occur because  $L_{dn}$  incorrectly accounts for human response to low-frequency noise (Fastl et al., 1996), and that supplemental metrics, such as SELA (time and number of events above a certain level), which are easier to understand, should be used for reporting airport noise. But here again the “level” is A-weighted.

Taken together, these concerns call into question whether community noise is being measured in the best way. Although modeling community responses to long-term exposure to environmental noise is somewhat different from investigating preferences in product sound, I believe lessons learned in perception-based engineering would be helpful in developing appropriate metrics for assessing community noise.

### A Mapping Initiative

A large noise-mapping initiative is under way in Europe, but we are not sure that appropriate metrics are being used to predict noise impacts or that the mapping process is flexible enough to update as we gain a better understanding of community response. Other questions have been raised about whether these maps will be interpreted correctly and whether it is possible to capture and convey the main attributes of an *acoustical* landscape (soundscape) in a visual representation (a map). Answering these questions may require a perception-based engineering project!

### Summary

Perception-based engineering is a people-focused approach to engineering design involving both stimulus-prediction (engineering) and stimulus-perception (psychology) modeling. To date, much of the focus has been on unimodal modeling, such as modeling force feedback and force perception in teleoperator applications (Choi and Tan, 2004) or sound quality in diesel engines (Hastings, 2004). Modeling human response to multiple modalities is more challenging, but necessary, to a more holistic approach to design (e.g., making trade-offs

between thermal and acoustic controls to maximize occupant comfort in energy-efficient buildings).

Engineers design and build machines and systems that have profound effects, both intended and unintended, on the quality of people's lives. Consider, for example, machines in intensive care units in hospitals that help save lives but may also disturb sleep, a key element in patient recovery. Engineers must take into consideration all of the impacts of their designs, and perception-based engineering is one discipline that can help them to do this.

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*Noise is a major driver in the design and operation of transportation systems.*

# Challenges and Promises in Mitigating Transportation Noise

Ian A. Waitz, Robert J. Bernhard, and Carl E. Hanson



Ian A. Waitz



Robert J. Bernhard



Carl E. Hanson

There are only a few places in the United States where transportation noise is not noticeable.<sup>1</sup> Figure 1 shows the results of an analysis estimating the percentage of each county in the United States where highway, rail, and aircraft noise are noticeable during the day (Miller, 2003). In 1981, the Environmental Protection Agency (EPA) estimated that 19.3 million people in the United States were exposed to a day-night average sound level ( $L_{dn}$ ) greater than 65 dB from highway traffic. The corresponding numbers

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<sup>1</sup> "Noticeability" is a function of the difference between the sound level of a specific transportation source and the background sound level in a community.

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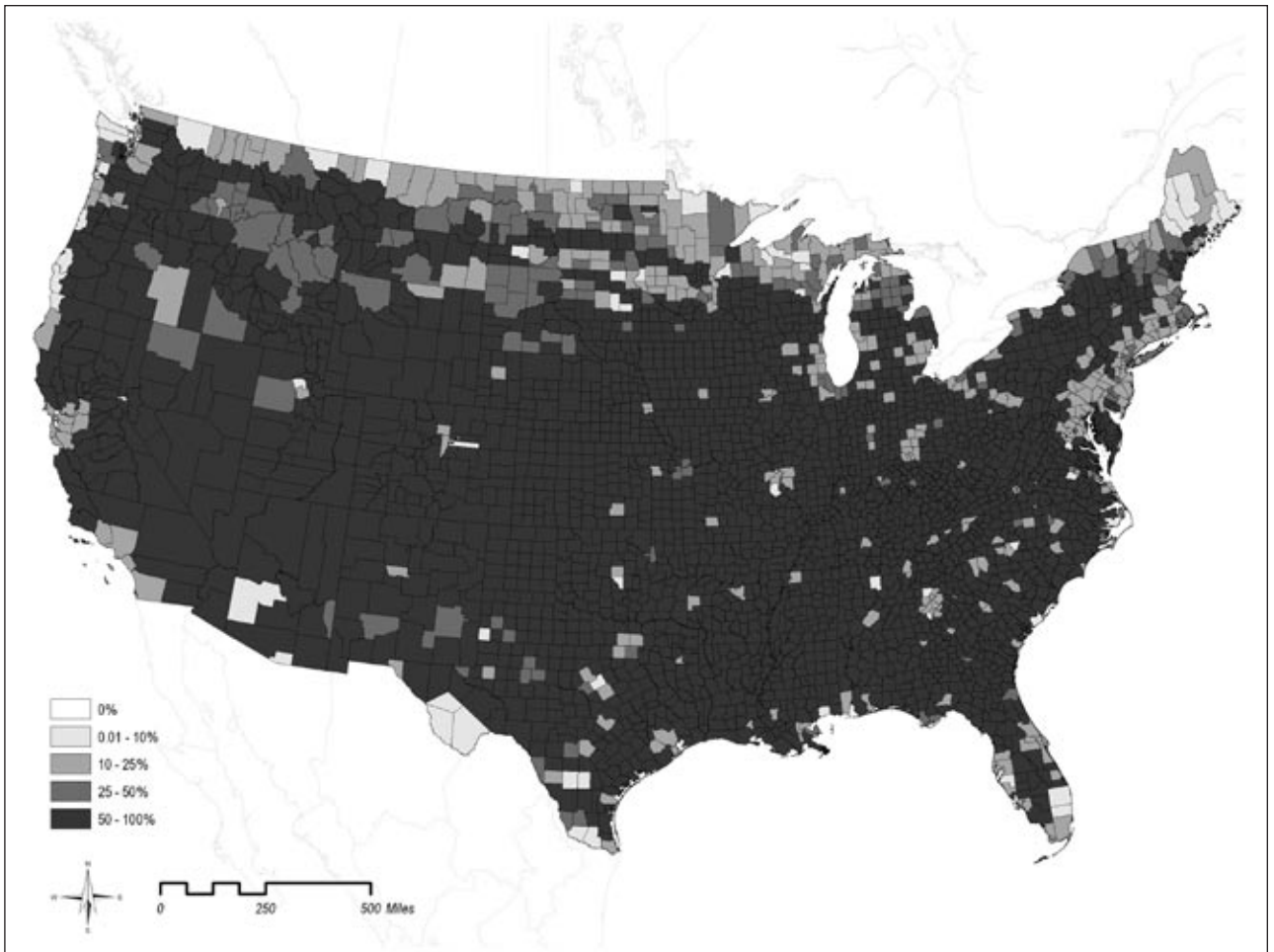


FIGURE 1 Percentage of each county that has noticeable noise from high-altitude aircraft, interstate rail traffic, or primary and secondary road traffic (whichever is highest). Local street traffic, considered background noise, can make the other sources less noticeable in densely populated areas (hence lower percentages may result for some of these areas). Source: Adapted from Miller, 2003.

for aircraft and rail were 4.7 million and 2.5 million, respectively.

Since the introduction of quieter aircraft, the number of people exposed to high levels of aircraft noise has dropped dramatically, to about 500,000. Updated figures for highway and rail noise are not available, but they may have increased with population growth and higher volumes of traffic.

Transportation noise can be annoying, disrupt sleep, interfere with communication, reduce property values, adversely impact health, and adversely affect academic performance. A comparison of noise annoyance from aircraft, road traffic, and rail noise based on exposure-response studies (Figure 2) showed that annoyance levels differed significantly for different modes of transportation (Miedema and Vos, 1998). When noise levels were less than 45 dB, the annoyance for all modes was

negligible, but they increased monotonically as a function of  $L_{dn}$ .

The rate of increase was found to be higher for aircraft noise than for either highway or rail noise. Factors believed to contribute to the differences include façade-exposure differences (noise on one side of a house from highway and rail noise as compared to all sides from aircraft), differences in onset rates, and differences in attitude.

Because large numbers of people are impacted by transportation noise, and because the impacts are significant, noise levels are important concerns in the design and operation of all modes of transportation. Transportation noise is frequently the dominant environmental concern voiced by the public about the development and expansion of transportation systems. In this article, we review some unique aspects of road,

railway, and aviation noise and describe some efforts to reduce the effects of noise to accommodate anticipated increases in demand for transportation.

**Issues Specific to Different Modes of Transportation**

*Highway Noise*

Highways are the most pervasive source of transportation noise. Effects range from disturbances of the natural soundscape in wilderness areas to sound levels near occupational safety limits for the exterior of residences close to high-capacity freeways.

Highway noise comes from several sources. Noise from engines, exhaust systems, and power trains tend to dominate for low-speed or accelerating conditions. Tire/pavement noise tends to be most important at typical freeway speed. Aerodynamic noise tends to dominate only in very high-speed situations that are not common in the United States.

Tire noise may be dominant for automobiles, even under cruising conditions on urban streets. For trucks, power-train noise is a major source of noise on arterial roadways, but tire/pavement noise tends to dominate at freeway speeds, where a heavy truck makes approximately as much noise as 10 cars. Thus, even when there are relatively few trucks on the road, truck noise tends to be more noticeable than automobile noise.

Highway noise policy is implemented through approval (or denial) of federal matching funds for highway projects. Federal policy states that matching funds may only be used for noise mitigation where (1) there is frequent human “use”; (2) where predicted noise levels approach the noise-abatement criterion (NAC), which is typically 67 dBA (A = A-weighted) for the worst single hour of the year for receptor locations near residences; and (3) where mitigation is feasible and reasonable.

Because noise at a level of 67 dB interferes with

speech, mitigation is a consideration only where it would be difficult to hold a conversation and where there is a fairly continuous stream of traffic. However, when sound-propagation effects and background noise are considered, only residences within 200 to 400 feet of a heavily trafficked highway are usually eligible for noise mitigation. In addition, the neighborhood must be fairly densely populated for mitigation to meet the reasonableness requirement.

Although speed limits and changes in vertical (e.g., raising or lowering elevation of the highway) or horizontal alignment (e.g., moving a highway farther away from a neighborhood) are allowable mitigation methods, the most common approach is sound-wall barriers, which create an acoustical shadow. The performance of barriers is limited, however, by diffraction effects at the barrier edges. Barriers must be constructed to break the line of sight between the source and the receiver and must be as close to either the receiver or source as possible to maximize noise attenuation. Typical sound-wall barriers cost \$1.3 to \$2 million per mile. Thus barriers are expensive and have limited benefits. Nevertheless, they are one of the few options currently available.

The level of tire/pavement noise depends on the combination of type of tire and type of pavement. For any given pavement type (e.g., Portland cement concrete,

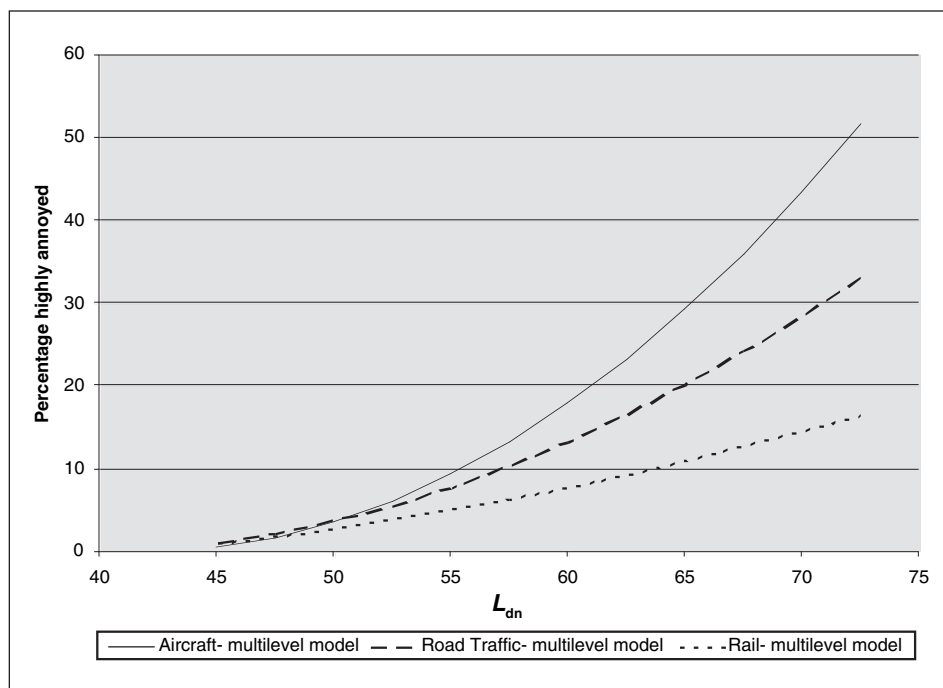


FIGURE 2 Percentage of highly annoyed people correlated with day-night average sound level (L<sub>dn</sub>) for three modes of transportation. Source: Miedema and Vos, 1998. Reprinted with permission of the Acoustical Society of America.

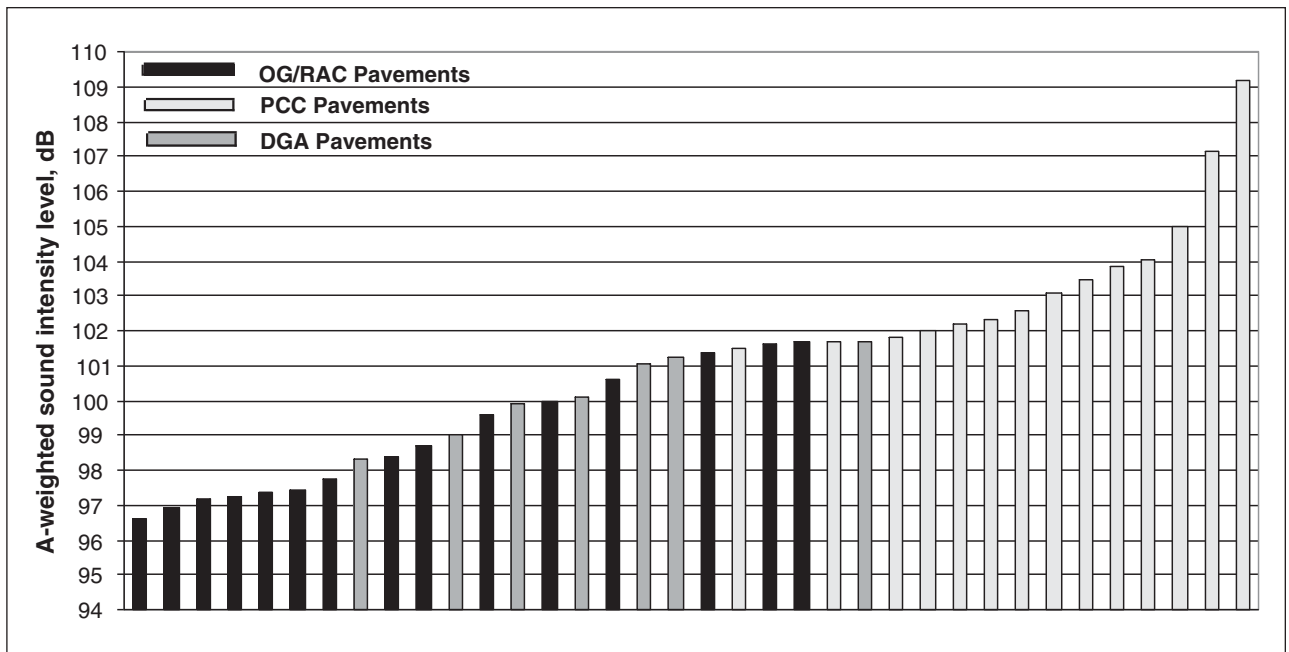


FIGURE 3 Sound-intensity levels on California highways measured by the onboard sound-intensity method. PCC = Portland cement concrete. DGA = dense graded asphalt. OG/RAC = open-graded/rubber asphalt concrete. Source: Donovan, 2005. Reprinted with permission of the Institute of Noise Control Engineering/USA.

asphalt) noise produced by different sections of roadway vary significantly, even with the same tires. Figure 3 is a compilation of tire/pavement noise generation measured on various California highways by microphone sensors near the tire. As the figure shows, there is a substantial difference between the loudest and quietest pavements. There is also significant variation for the same type of pavement caused by differences in construction and the condition of the pavement.

#### Aviation Noise

Of the noise from the three transportation modes under discussion, aircraft noise is typically the most localized. Annoying levels of aircraft noise are limited largely to areas within several miles of airports, although concerns about noise from aircraft at cruising altitudes have arisen in National Parks and other quiet areas.

As noted above, on a per dB basis, people consider aircraft noise more annoying than noise from surface modes of transportation. We do not know how much this difference is related to physical and physiological factors as compared to public perceptions and other factors.

Aviation noise results from a combination of acoustic energy generated by unsteady fluid-mechanical processes in aircraft engines, noise generated from the unsteady interaction of exhaust jets and/or propellers with the surrounding air, and noise related to unsteady

flow produced by the airframe. Takeoff and approach noise are the primary sources of community complaints. The former is dominated by engine noise, whereas the latter is dominated by a combination of airframe and engine noise.

The most dramatic reductions in transportation noise have been in aviation. As shown in Figure 4, in the last 35 years, the number of people in the United States impacted by aviation noise has been reduced by 95 percent, even though there has been a six-fold growth in air-transportation mobility (as measured by the number of people-miles traveled) (Waitz et al., 2004). Today, fewer than 0.5 million people in the United States are impacted by aircraft noise of greater than 65 dB  $L_{dn}$  (and fewer than 5 million at greater than 55 dB  $L_{dn}$ ), even though there were 750 million enplanements this year alone.

This dramatic improvement in noise performance is the result of technological advances, the most significant of which was the introduction of high-bypass-ratio turbofan engines (introduced because of their superior fuel efficiency). The technological improvements were promoted by new certification standards included in the Airport Noise and Capacity Act of 1990, which mandated a phase-out of 55 percent of the older, noisier, fleet. The phase-out is estimated to have cost the U.S. airline industry \$5 billion (GAO, 2004).

Most projections suggest that continuing technological and operational advances in noise reduction will not keep pace with the growing consumer demand for air travel. Thus modest increases in the number of people impacted by aviation noise are anticipated.

Despite the reductions in noise described above, noise is still the environmental issue of most concern for airports (GAO, 2000), and a growing number of noise-related operating restrictions and fees are being imposed on airlines (Boeing Commercial Aircraft, 2006). Communities surrounding some airports have taken steps to delay or cancel airport-expansion plans or impose operating restrictions, such as flight-path restrictions and curfew hours during which operations are not permitted. One example of a delay is the runway expansion at Logan International Airport in Boston. In the early 1970s, construction of a half-built runway was halted by a court injunction that remained in place for 30 years.

In the United States, we also spend approximately \$300 million a year, collected from fees and taxes on airline tickets, to insulate homes and purchase land around airports in areas where aircraft noise levels exceed 65 dB  $L_{dn}$  (NRC, 2002). However, most of the population exposed to aviation noise lives outside these areas.

*Railroad and Urban-Transit Noise*

In 1981, it was estimated that 2.5 million people were exposed to railroad and urban-rail noise. Considering the explosive growth in railroad operations in recent years and the increase in track miles of urban-transit systems, that number is probably greater today. In addition, a recent study by the Federal Railroad Administration (FRA) estimated that more than 9 million people are impacted by noise from train horns at the 154,000 grade and highway crossings in the United States (DOT, 2002).

The impact of rail noise from operations is confined

to relatively narrow corridors, but, because urban-transit systems are located in densely populated cities, they expose large numbers of people to significant noise levels. Within a few hundred feet of surface or elevated tracks, noise levels can exceed 85 dBA, which is high even in the context of a typical urban-noise environment. Despite the potential effects of rail-transit noise on people in cities, EPA estimates that noise exposure from rail transportation is mostly from railroad freight operations and freight yards, which, together, accounted for 80 percent of the total rail-noise exposure in 1981.

Noise generation from rail systems can be divided into two categories: moving sources and stationary sources. Noise generated by moving sources, such as trains traveling on tracks, include propulsion noise from diesel engines or electric motors; mechanical noise from fans, compressors, and auxiliary units; wheel/rail noise from rolling, impact, and squealing; and aerodynamic noise from turbulent boundary layers, vortex shedding, and wakes.

Stationary sources in fixed locations include noise at road crossings from horns and bells; noise from layover tracks from idling diesel engines; and yard noise from retarders, car couplers, and idling locomotives. Poorly

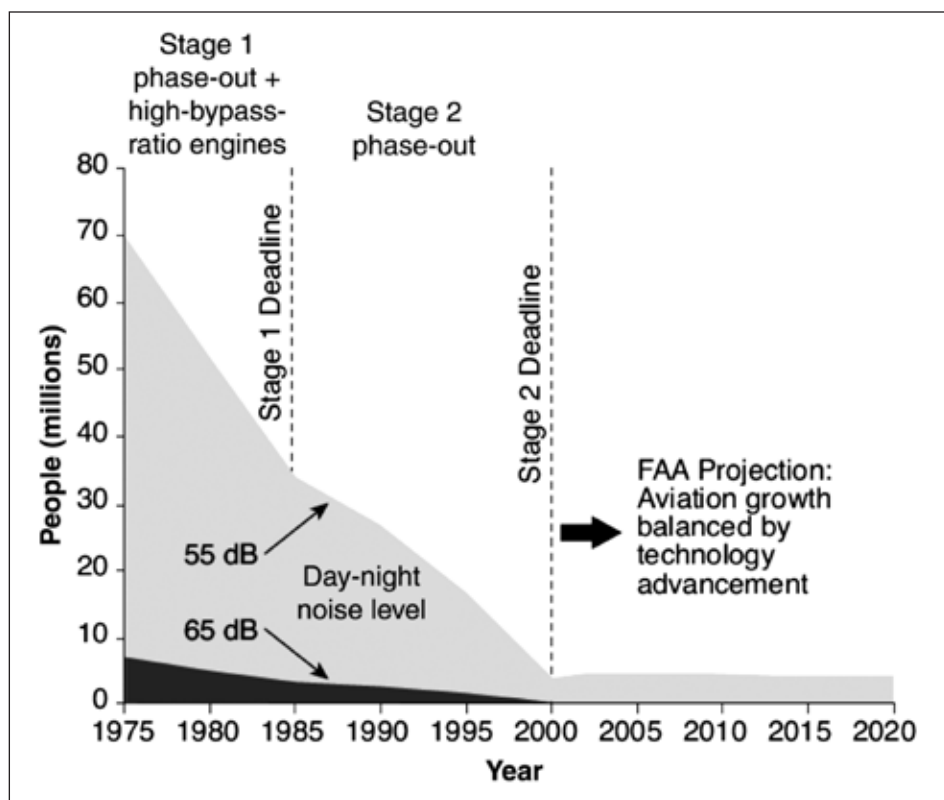


FIGURE 4 Estimated number of people affected by aircraft noise in the United States. Source: Waitz et al., 2004.

maintained vehicles and facilities are the root cause of excessive noise from both railroads and urban-rail systems. Flat spots on steel wheels, rough rail-running surfaces, and misaligned rail joints can increase noise levels by 10 dBA compared to well maintained systems. Deferred maintenance is often the result of budget shortfalls, especially in urban transit systems.

Unlike highway vehicles and aircraft, rail transportation generates significant ground-borne vibrations that are often associated with noise. The pass-by of a heavily loaded train causes ground vibrations that are transmitted to nearby buildings where they can be felt as physical shaking or heard as a rumbling sound. People often misinterpret ground vibration as noise. Vibration is generally a problem only a short distance from the tracks, but it can interfere significantly with activities that require low-vibration environments.

In 1987, the Federal Transit Administration (FTA) issued a joint regulation with the Federal Highway Administration for mitigating adverse noise impacts from rail transportation. The regulation states that mitigation measures are eligible for funding when FTA determines that “. . . the proposed mitigation represents a reasonable public expenditure after considering the impacts of the action and benefits of the proposed mitigation measures” (DOT, 1987). Noise from freight railroad operations and yards is regulated by standards developed by EPA and enforced by FRA (EPA, 2003).

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*Quieter pavements can have the same safety, durability, and cost as current pavements.*

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Several local transit agencies have developed their own policies for mitigating noise and vibration impacts. Chicago Metra has adopted a general policy statement on mitigating noise and vibration with criteria consistent with FTA criteria and a strategy for implementation of cost-effective mitigation measures. The Metropolitan Boston Transit Authority (MBTA) and other transit agencies have adopted similar policies on a project-by-project basis.

## **Mitigating Noise in the Future**

### *Highway Noise*

As shown in Figure 3, pavements can be made significantly quieter. Based on data collected to date, substantial improvements in pavement types can be made by improving how they are built and maintained. In addition, novel quiet-pavement concepts have been demonstrated that are several decibels quieter than the quietest sections of pavement shown in Figure 3 (Sandberg and Ejsmont, 2002). The general strategy for quieter pavements is to make them porous and somewhat elastic with as little positive texture as possible. These pavements can be constructed to have the same safety, durability, and cost characteristics as pavements constructed with current technology.

Tires are not typically designed to minimize radiated noise. Although automobile tires can be made quieter, the improvement would generally mean lower durability and/or higher cost.

Sound-wall barrier design is fairly mature. However, the performance of barriers could be improved by building them taller and closer to the noise source, which might entail building a partial tunnel for the highway.

Studies on understanding the causes of “annoyance” are ongoing. For highway noise, outlier events, such as air-compression braking by trucks and poorly maintained exhaust systems, increase annoyance. Tonal sounds from the periodic texturing of pavement or uniform tread-block sizes also increase annoyance. Spectral and temporal engineering of the radiated sound could reduce annoyance levels without necessarily reducing sound-pressure levels.

### *Aviation Noise*

We will need a balanced approach to make further reductions in community noise from aircraft. This approach must include technological advances, operational advances, and better land-use planning around airports. The latter presents many challenges, and there are many examples where federal guidelines for land use have not been followed, exacerbating community noise problems. Even when airports are located in sparsely populated areas (e.g., Dallas/Fort Worth International Airport and Denver International Airport), local decisions often lead to increased land use in areas with high aircraft noise. It is not clear how these issues will be addressed in the future, but several airport communities have developed effective forums for addressing these issues proactively (e.g., San Francisco

Community Roundtable and O'Hare Noise Compatibility Commission).

Near-term improvements are most likely to come from operational advances. The Federal Aviation Administration is working with airports and airlines to implement continuous-descent arrivals, which require aircraft to approach airports on steeper descents with lower, less variable throttle settings. This type of descent has been shown to reduce noise, burn less fuel, and reduce emissions (Clarke et al., 2006). However, noise reductions from operational measures are likely to be limited.

Technological improvements will be necessary for more significant reductions in noise. Evolutionary improvements in technology are likely to continue to reduce noise from aircraft engines and airframes at a rate of 2 to 3 dB per decade. Step-change technologies (e.g., aircraft with noise signatures quieter than typical background urban and suburban noise levels) are also being investigated by academia, industry, and government (e.g., Hileman et al., 2007), but many economic and technological risks are still unresolved. Such technologies are not expected to be introduced for at least 15 to 20 years. Despite the significant technological opportunities for reducing aviation noise, federal funding for basic research in this area has decreased markedly in the last 10 years (NRC, 2002).

Low-noise technology and operational measures must be considered in the context of trade-offs with fuel efficiency and emissions, because other environmental concerns, such as climate change and local air quality, must also be addressed.

#### *Railroad and Urban-Rail Transit Noise*

Noise control for conventional rail systems is often a matter of good, timely maintenance. Wheel/rail noise can be minimized by ensuring that running surfaces are smooth. In urban transit systems, wheel truing and rail grinding are key elements in controlling noise. Special treatments for controlling squealing noise on curves have resulted as a side benefit of friction-management programs. Research on optimum shapes for very-high-speed trains has contributed to our understanding, and eventual control, of aerodynamic noise sources that dominate noise from trains moving at speeds of more than 150 mph.

Because noise has been identified as a key issue associated with environmental assessments for new rail systems, both FTA and FRA have made guidelines available for assessing noise and vibration. FTA's guidance manual,

*Transit Noise and Vibration Impact Assessment*, includes criteria and procedures for determining impacts and mitigation measures for excessive noise and vibration in projects funded by FTA under its policy for implementing environmental-mitigation measures (DOT, 2006a).

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## *Trade-offs are necessary to address noise-reduction, environmental, and safety concerns.*

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FRA's manual, *High-Speed Ground Transportation Noise and Vibration Impact Assessment*, provides similar information for high-speed rail projects (DOT, 2005). Both manuals have been instrumental in encouraging planners of new rail systems to take noise control into account.

Another policy development in controlling noise from rail systems is a recently enacted rule for using locomotive horns at grade crossings (DOT, 2006b). The rule protects public safety by requiring the use of horns but also establishes maximum horn-noise levels, limits on the duration of horn use, and guidelines for implementing quiet zones. Many communities have taken steps to reduce or eliminate horn noise by following these guidelines.

Sound insulation for homes impacted by rail noise has not been developed to the same extent as it has for homes near airports. The MBTA commuter railroad conducted pilot studies on houses near grade crossings where horns are blown but where noise barriers are impractical because of sight-line requirements. These studies have resulted in recommendations for treating homes where mitigation would be practical. Another example is Chicago Metra, which has included sound insulation in its noise policy. Nevertheless, these agencies are exceptions to the general rule.

#### **Summary**

Transportation sources dominate the noise environment in many regions of the United States. The greatest number of people is exposed to impact levels of highway noise, followed by rail noise, and then by aviation noise. However, on a per dB basis, aircraft noise is estimated to be most annoying. Thus aircraft noise is a

severe problem in areas near airports, whereas highway and rail noise are more widespread problems.

A positive trend in reducing transportation noise is that aircraft have become dramatically quieter as the result of technological improvements, and noise contours around airports have shrunk commensurately. However, with aviation operations projected to triple by 2020 and sometimes-conflicting requirements for aircraft fuel efficiency and emissions, it remains to be seen if this trend will continue.

Another positive trend is tire-pavement research to reduce highway noise at the source instead of installing noise barriers, which shield only localized areas. For rail noise, agency guidelines developed for identifying problems early in the project development stage are being used throughout the United States to reduce the impact of noise. Many federal, state, and local transportation agencies are adopting and implementing noise-mitigation policies, and noise is a major consideration in the design and operation of all transportation systems.

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*When purchasing equipment, industry leaders often fail to take into account the risk to hearing.*

# Engineering Controls for Reducing Workplace Noise



Robert D. Bruce is principal engineer, Collaboration in Science and Technology Inc., Houston, Texas.

Robert D. Bruce

**M**illions of workers in the United States are exposed to sound levels that are likely to cause permanent hearing loss, even though many of them wear hearing-protection devices. Many people do not realize that these devices and hearing-protection programs are *not* the preferred way of protecting hearing. The preferred way, often called “engineering controls,” is to reduce the noise of machinery or introduce a noise control element between machinery and workers.

Engineering controls are preferred for many reasons, including permanence, effectiveness with or without worker/supervisor compliance, less absenteeism, easier communication, lower worker compensation costs, and reduced legal costs. In fact, engineering controls are the protection method of choice according to the Occupational Safety and Health Administration (OSHA).

This paper reviews the use of engineering controls for existing noise sources in American workplaces. Many of these controls could be integrated into machinery by original equipment manufacturers, but, for non-engineering reasons, they have been eliminated from the machinery design.

Since the late 1940s, scientists and engineers have been working on ways to control noise from machinery. In the 1970s, the emphasis was on engineering controls in the workplace, but since then the focus has shifted because OSHA has not enforced the requirement for engineering

controls and because industry leaders have failed to take into account the risk to hearing when purchasing equipment.

### Occupational Noise-Exposure Regulation

The OSHA Regulation (often called Standard) 29 CFR Occupational Noise Exposure-1910.95 is excerpted below:

#### 1910.95(b)(1)

When employees are subjected to sound exceeding those listed in Table G-16, feasible administrative or engineering controls shall be utilized. If such controls fail to reduce sound levels within the levels of Table G-16, personal protective equipment shall be provided and used to reduce sound levels to within the levels of the table.

#### 1910.95(b)(2)

If the variations in noise level involve maxima at intervals of 1 second or less, it is to be considered continuous.

**TABLE G-16**  
**Permissible Noise Exposures (1)**

Duration per day, hours	Sound level dBA slow response
8	90
6	92
4	95
3	97
2	100
1-1/2	102
1	105
1/2	110
1/4 or less	115

Footnote(1) When the daily noise exposure is composed of two or more periods of noise exposure of different levels, their combined effect should be considered, rather than the individual effect of each. If the sum of the following fractions:  $C(1)/T(1) + C(2)/T(2) + \dots + C(n)/T(n)$  exceeds unity, then, the mixed exposure should be considered to exceed the limit value.  $C_n$  indicates the total time of exposure at a specified noise level, and  $T(n)$  indicates the total time of exposure permitted at that level. Exposure to impulsive or impact noise should not exceed 140 dB peak sound pressure level.

Note that the regulation calls for engineering controls to be used first to reduce sound levels to within the limits specified in Table G-16, and, only if the controls do not succeed in bringing the sound levels down are hearing-protection devices to be used in addition.

The requirement is that “feasible administrative or engineering controls” be tried. Simply explained, “administrative control” means removing workers from noise exposure by rotating them from noisy to quieter areas. “Feasible” means what it always means—that it can be done. However, sometimes the cost of a noise control treatment is cited as a reason it is “not feasible” for a particular company to install it.

A number of very simple engineering controls can often be implemented with great success:

- proper maintenance (e.g., fixing steam leaks)
- modified operating procedures (e.g., relocating an operator and equipment controls to a quieter position)
- relocation of noisy vents away from workers
- replacement of equipment (e.g., buying a quieter version of the product)
- modified room treatment (e.g., introducing sound absorption in the space between equipment and worker to reduce noise in the distant reverberant field)
- relocation of equipment (e.g., putting noisy equipment in areas that are often unoccupied)
- proper operating speed (e.g., running equipment at lower speed to reduce noise)

Despite the effectiveness and ease of taking these simple actions, they are often ignored.

### Noise Sources Involving Fluid Flow

Noise sources that involve fluid flow include fans, compressors, engines, pumps, and valves. The most frequent problem is sound from the discharge, but engineering solutions (e.g., lined ducts; dissipative and reactive silencers; and special-purpose silencers) are available for both intake and discharge noise.

Ducts can be lined with sound-absorbing material, such as fiber glass or mineral wool. Typical thicknesses are 1 to 4 inches. Thicker materials are used for low-frequency noise.

Dissipative silencers involve using sound-absorbing materials, such as mineral wool or fiber glass, to attenuate noise. A simple dissipative silencer would be a

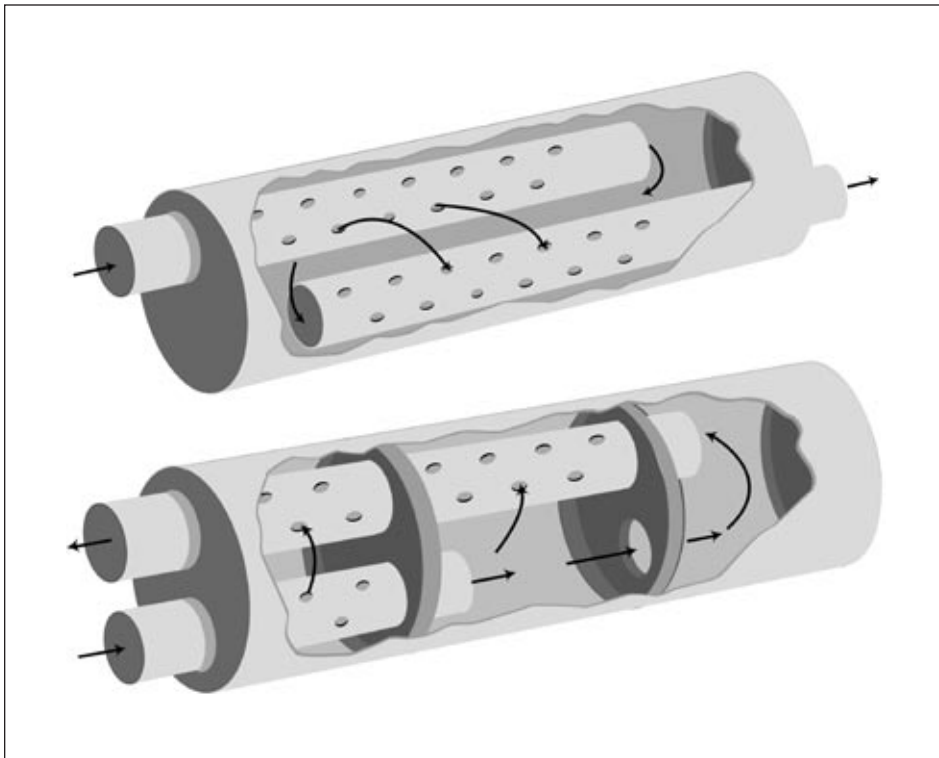


FIGURE 1 Diagram of reactive mufflers showing expansion chambers.

series of parallel baffles running lengthwise from a noise source that requires airflow. The absorptive material would likely be covered with glass-fiber cloth to reduce erosion caused by airflow, and perforated or expanded metal might be added to protect against contact damage. The silencer could be improved by using longer baffles and decreasing the space between them.

Reactive silencers operate on the basis of mismatching acoustic impedance. Whenever a sound wave meets a change in the acoustic impedance, some of its energy is reflected back to the source or back and forth within the silencer. An example of a reactive muffler is shown in Figure 1.

Recently, a special-purpose silencer was developed based on the principles of a Helmholtz resonator (a small neck and a larger cavity, such as a bottle). As sound waves pass over the opening of the neck, a small portion of gas at the neck of the bottle begins to oscillate back and forth. The frequency at which this “slug” of gas oscillates is a function of mass-spring resonance—the slug in the neck acts as the mass, and the volume of gas in the cavity acts as the spring. This resonance is a function of the diameter of the neck, the density of the gas, the length of the neck, the volume of the cavity, and the speed of sound in the gas.

The resonance frequency in Hz of a simple Helmholtz resonator can be calculated from the following expression:

$$f = \frac{1}{2 \pi (M C)^{0.5}}$$

$M = \rho \ell / A$  ( $\rho$  = the gas density ( $\text{kg}/\text{m}^3$ )),  $\ell$  = the “effective” length of the neck (m), and  $A$  = the cross-sectional area of the neck ( $\text{m}^2$ ).  $C = V/\rho c^2$  ( $V$  = the volume of the cavity ( $\text{m}^3$ ),  $\rho$  = the density ( $\text{kg}/\text{m}^3$ ), and  $c$  = the speed of sound (m/s) in the gas).

The ends of the tube influence the resonance frequency by increasing the effective length ( $\ell$ ) of the neck. Note that the resonance frequency is independent of density. The resonance frequency of a typical 500 ml water

bottle, about 200 Hz, can be excited by blowing across the top of the bottle.

One special-purpose silencer, invented by Liu (2003) of Dresser-Rand, uses the Helmholtz concept to reduce centrifugal compressor noise, which often includes a strong tonal component at the blade-passing frequency of the compressor. The resonators for the Dresser-Rand Duct Resonator Array (DRA) are shown in Figure 2.

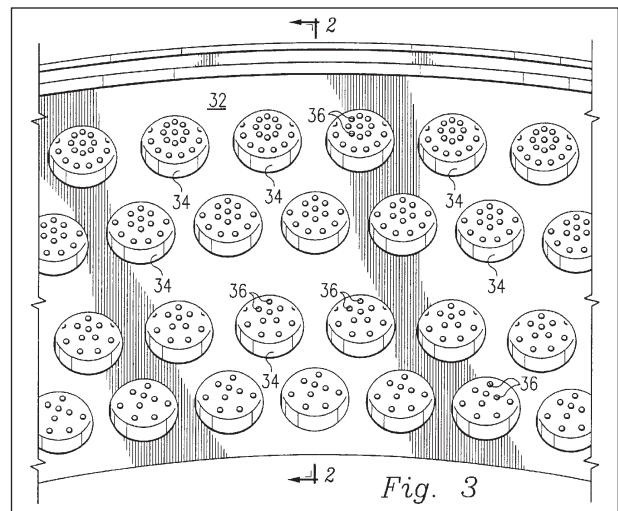


FIGURE 2 Dresser-Rand Duct Resonator Array (per patent 6,550,574 B2).

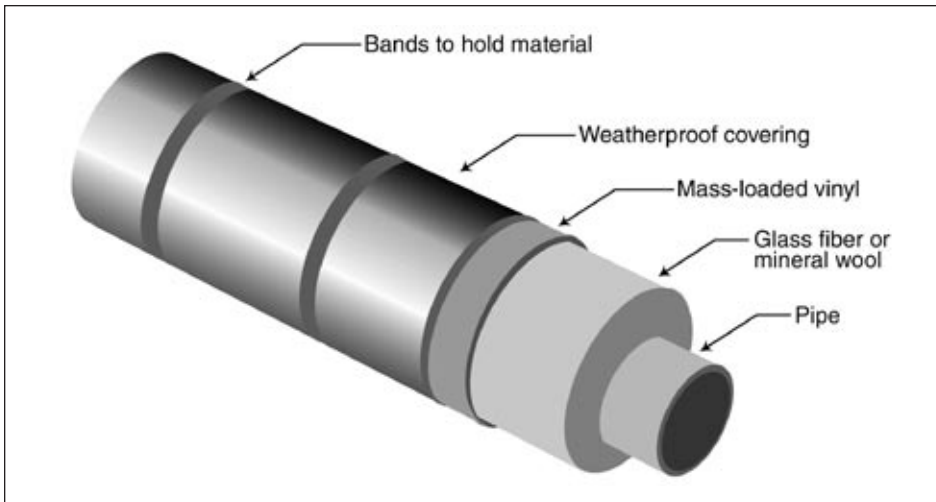


FIGURE 3 Pipe lagging.

The numerous holes in the resonators, acting as masses in parallel, raise the resonance frequency. The cavity behind these holes acts as the volume for the resonator. The DRA, which consists of numerous resonators positioned at the diffuser of the compressor, can also be located in a pipe spool in discharge piping. The DRA reduces the A-weighted sound level by at least 10 dB—which is similar to “halving” the loudness of the sound.

Significant noise radiating from piping in refineries and from forced-draft and induced-draft fan ducts can be reduced simply with layers of treatment around the piping (Figure 3). Typically, the first layer is 2 to 4 inches of 6 to 8 lbs/ft<sup>3</sup> glass fiber or mineral wool wrapped around the pipe. Next a mass-loaded vinyl or lead sheeting weighing 1 to 2 lbs/ft<sup>2</sup> is wrapped around the glass fiber or mineral wool. Finally, a weatherproof covering is added. This type of treatment can provide 10 to 20 dBA of noise reduction, depending on the details of the installation.

### Radiated Noise from Machinery Housings

Airborne noise can radiate from any surface. In a piano, for example, the keys strike the hammers, which hit the strings. Although the strings do not produce much sound by themselves, they are attached to the soundboard, which is very large compared to the strings and radiates the sound. In general, the larger the vibrating panel, the more sound is radiated from the surface.

Another example is a metal parts bin into which metal parts are dropped. If the bin is made of perforated, rather than solid metal, the radiating area, and thus the radiated sound, is reduced. Of course, materials

with high internal damping radiate less noise. If the bin were made of rubber (with high internal damping) rather than metal (with low internal damping), the radiated sound would be reduced accordingly.

Sometimes machinery is housed inside an enclosure provided by the original equipment manufacturer. If there is any possibility that the resonance frequencies of the enclosure panels will be excited, it is desirable that the housing be treated

with a damping material. If the machine inside the enclosure causes significant vibration of the enclosure housing and structure, then the panels should be “vibration-isolated” from the structure. In addition, it may be useful for the machinery enclosure to be mounted on vibration isolators to minimize the amount of vibration transmitted to the floor.

### Machinery Shields

An acoustical shield may be inserted between the worker and a noisy section of a machine. An acoustical shield, often mounted on the machine, can provide 8 to 10 dB of noise reduction under the following circumstances: the worker is near the noisy operation; the smallest dimension of the shield is at least three times the wavelength of the dominant noise; and the ceiling above the machine is covered with sound-absorptive material.

Shields can be manufactured from safety glass, quarter-inch thick clear plastic, metal, or wood. Criteria for selecting materials include durability, cost, the need for visual observation of the operation, and the need for physical access to the operation. If possible, oil-resistant, cleanable, sound-absorptive materials should be incorporated into the machine side of the shield.

Handles and casters can be provided to facilitate moving of the shield, and hinged sections can be incorporated into the design to provide physical access to the machine. Neoprene can be used to minimize acoustical leaks through joints or hinges.

When shields are used to replace less acoustically efficient machine guards, the shield should be fitted

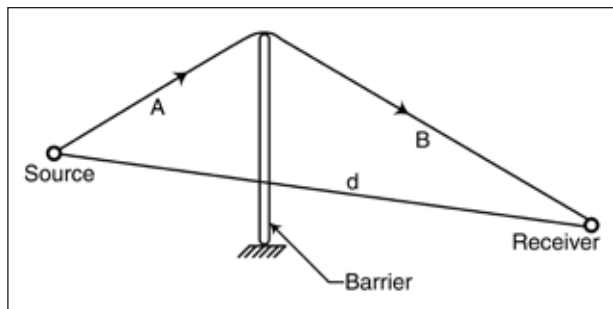


FIGURE 4 Geometry for determining sound attenuation by a noise barrier (*d* is the straight line distance from source to receiver and *A+B* is the shortest path length of wave travel over the wall between source and receiver).

carefully to cover all noise leaks and then vibration-isolated to keep the shield from vibrating with the machine and thus radiating sound.

**Barriers**

Any solid wall that blocks the line of sight between a noise source and an observer will reduce the noise level at the location of the observer. The noise reduction depends on the frequency of the noise, the distance between the source and the wall, the distance between the receptor and the wall, and the height of the wall. Low-frequency sound, which has wavelengths comparable to the size of the wall, diffracts around the ends and over the top. Thus, low-frequency sounds are less attenuated than high-frequency sounds. Typically, low-frequency sounds are attenuated by less than 5 dB, whereas high-frequency sounds can be attenuated by as much as 20 dB.

The highest practical value for barrier attenuation is 24 dB. If the noise source is inside a room, then the barrier effect may be reduced, depending on the room absorption and the location of the receivers relative to the barrier wall.

Most formulas for calculating the attenuation provided by a barrier assume that the wall is infinitely long. One typical calculation procedure uses the difference between a direct path from the source to the

receiver and the path over the barrier (Figure 4). This difference is called the “path length difference.”

Attenuation =  $10 \log (3 + 0.12 f P)$ , where *f* = the frequency in Hz, and *P* is the path difference in meters (*A+B-d*).

**Partial Enclosures**

A partial enclosure is a series of walls around a machine with the top left open. This treatment can be effective inside a plant for positions near a wall. However, some of the noise radiates out the open top and contributes to the reverberant sound in the room. Reflections from the ceiling increase the sound level at greater distances from the barrier (Figure 5).

For a 10 dB reduction, the angle shown in the figure must be greater than 30°, and the ceiling must either be sound absorptive or 1.5 times the distance from the source to the receiver. A sound-absorptive ceiling can reduce reflected sounds, thereby increasing the effectiveness of the barrier. For maximum effectiveness, the sound-absorptive ceiling should extend out to the location of the receivers, and the inside of the barrier walls should be sound absorptive.

**Total Enclosures**

A total enclosure with a closed top will provide better noise reduction than a partial enclosure. However, enclosures usually need openings to provide access for personnel (e.g., visual, maintenance, operator usage);

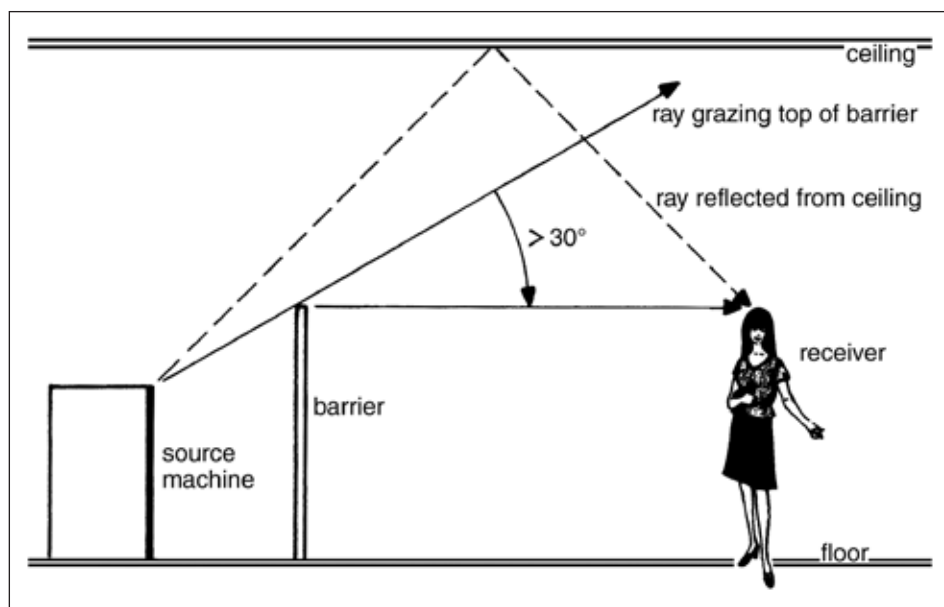


FIGURE 5 Source-barrier-receiver geometry for an indoor noise source.

access to materials (e.g., raw materials, product, scrap removal); and ventilation.

Leaks around doors, windows, and hatches greatly reduce the acoustical effectiveness of enclosures. Closed-cell elastomeric weather-stripping with a pressure-sensitive adhesive can be used to prevent sound leakage from around doors, windows, and hatches. Special acoustical gaskets are available, as well as magnetic-strip gaskets similar to those used on refrigerator doors.

If workers need to be able to see inside an enclosure, lighting may be required. If workers evaluate the performance of the machinery by its sound, it may be necessary to retrain them or to place a rugged microphone inside the enclosure that sends a signal to a small adjustable loudspeaker at the worker position. Occasionally, it is possible to develop processors that incorporate workers' knowledge to automatically adjust the machinery for optimal performance.

Openings for raw materials, products, and scrap-flow can be tunnels lined with sound-absorptive material. The noise reduction will depend on the length and cross-section of the tunnel, as well as the thickness of the sound-absorptive material.

Ventilation is required for all total enclosures and for some partial enclosures. The amount of air required for cooling is a function of the heat generated within the enclosure, as shown in the following equation:

$$Q = 1.76 W/\Delta T$$

$Q$  = the flow of cooling air in cubic feet per meter at sea level,  $W$  = the watts of

heat generated, and  $\Delta T$  = the temperature rise permitted above the ambient temperature ( $^{\circ}\text{F}$ ). Ventilation openings can be acoustically lined ducts, elbows, or mufflers, depending on the severity of the problem. Machinery with special heat-sensitive equipment may require special cooling.

Neither the enclosure panels nor the enclosure structure should be in contact with any part of the machinery. If the enclosure is mounted on the machinery, it should be vibration-isolated from the machinery. All holes in the enclosure for electricity, oil, water, steam, air, or

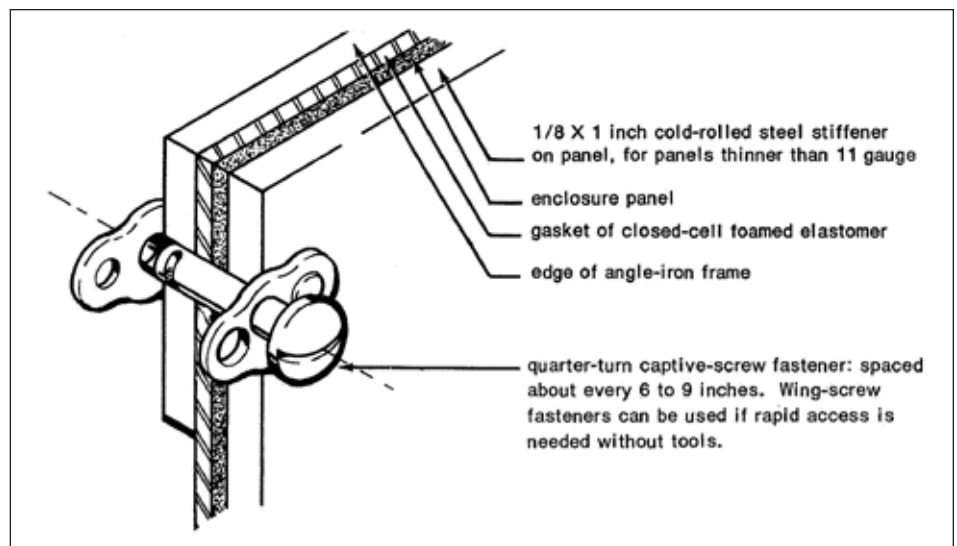


FIGURE 6 Enclosure panels secured to frame by quarter-turn fasteners.

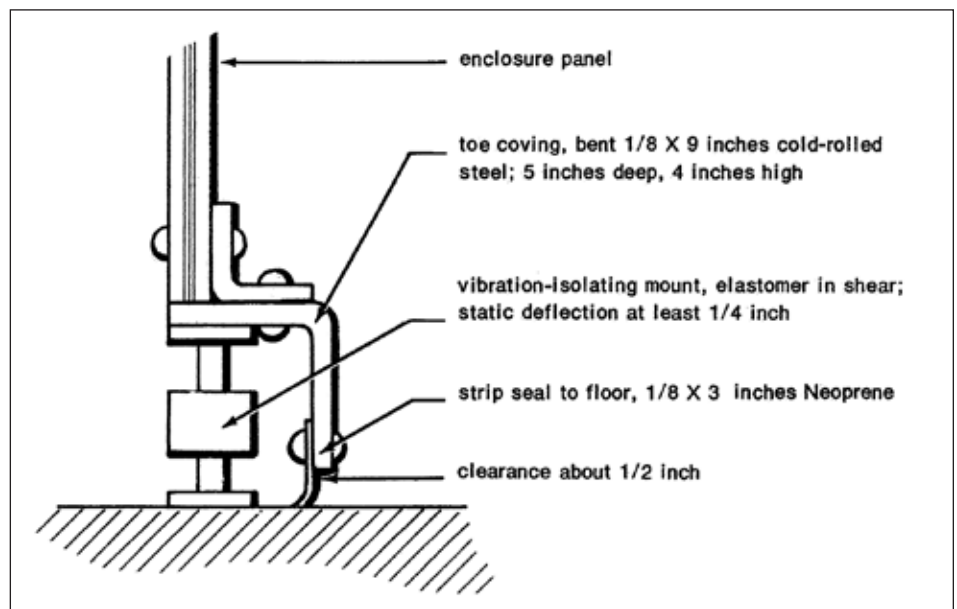


FIGURE 7 Vibration isolation and toe covering.

hydraulic power must open into a junction box packed and sealed with at least 3 inches of glass fiber.

A convenient design can be built on an angle-iron frame to which the enclosure panels can be attached with quarter-turn captive screws. The enclosure should be as small as possible without touching the machinery. Noise reductions of 20 dB can be obtained with careful attention to design and construction.

Figure 6 shows the connection of the panels to the angle iron frame. Damping and sound-absorption material are attached to the interior of the panel.

The enclosure should also be vibration-isolated from the floor (Figure 7). If the machine vibrates, it may also be important to isolate it using steel springs or elastomers, depending on the circumstances.

If the enclosure panels are metal, their resonances can be distributed uniformly in frequency if the panel is reinforced by bolted-on angle irons (bolting adds damping). These stiffeners should be placed to divide the panel into smaller areas, no two of which are the same size and shape. Frames for doors, windows, and hatches can also be used as stiffeners.

Windows are an acoustical weak link in enclosures. Generally, if the A-weighted sound level must be reduced by more than 20 dB, double-glazing will be necessary. The inside layer, which must withstand rough handling and cleaning to remove oil, grease, and dirt, should be safety glass. All panes should be set into soft elastomer gaskets. Room-temperature-setting silicone rubbers are useful. The window(s) should be placed carefully to provide the necessary information to the operator. In extreme cases, closed-circuit video monitoring can be used.

If the dimensions of the enclosure result in resonance, the enclosure can be driven to high levels of vibration and become a new radiator of these sound components. When the enclosure is driven to high levels of vibration, the sound-pressure level outside the enclosure can be higher than it was before the enclosure was installed. If the noise source occupies a sufficient fraction of the

room volume, this effect can be significantly reduced by using absorbent lining on the interior surfaces of the enclosure and by stiffening the panels and lining them with damping materials.

## Summary

As these brief descriptions show, engineering controls are available for use in industries today! As Liu of Dresser-Rand has shown, the development of innovative noise control treatments provides opportunities for applying basic physics and engineering. Like any other engineering problem, noise control requires detailed work—first to identify the source, then to determine the most effective noise control technique, and then to determine the most cost-effective solution. However, like any other purchase, quality costs.

**Note:** Numerous books and publications are available for reference. For formulae and specific applications see Berger et al., 2000; Bies and Hansen, 2003; Bruce and Bommer, 2004; and Jensen et al., 1978.

## References

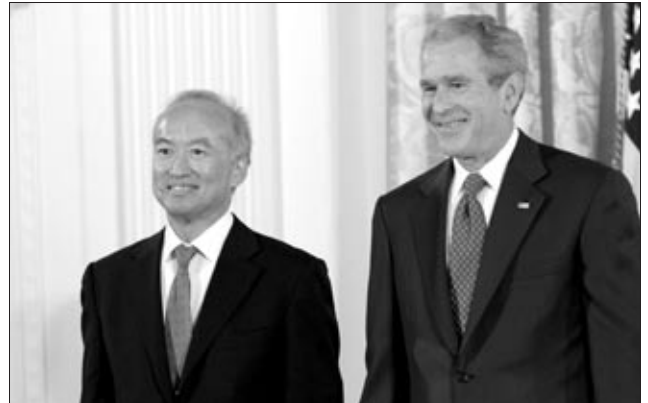
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# NAE News and Notes

## Eight NAE Members Receive National Medals of Science and Technology\*



Jan D. Achenbach, 2005 National Medal of Science Laureate



Alfred Y. Cho, 2005 National Medal of Technology Laureate



Robert Langer, 2006 National Medal of Science Laureate



Leslie A. Geddes, 2006 National Medal of Technology Laureate

President George W. Bush presented the 2005 and 2006 National Medals of Science and National Medals of Technology at a White House ceremony on July 27, 2007.

A **2005 National Medal of Science** was awarded to **Jan D. Achenbach**, Distinguished McCormick School Professor, Center for Quality Engineering and Failure Prevention, Northwestern University, “for his seminal contributions to engineering research and education in the area of wave propagation in solids and for

pioneering the field of quantitative non-destructive evaluation.”

A **2005 National Medal of Technology** was awarded to **Alfred Y. Cho**, vice president (retired), Semiconductor Research Laboratory, Bell Laboratories, Alcatel-Lucent, “for his contributions to the invention of molecular beam epitaxy (MBE) and the development of MBE technology into an advanced electronic and photonic devices production tool, with applications to cellular phones, CD players, and high-speed

communications over the course of three decades.”

A **2006 National Medal of Science** was awarded to **Robert Langer**, Institute Professor, Massachusetts Institute of Technology, “for revolutionary discoveries in the areas of polymeric controlled release systems and tissue engineering and synthesis of new materials that have led to new medical treatments and have profoundly affected the well-being of mankind.”

All five of the **2006 National Medals of Technology** were awarded

\*Photos courtesy of the National Science & Technology Medals Foundation.



Paul G. Kaminski, 2006 National Medal of Technology Laureate



Herwig Kogelnik, 2006 National Medal of Technology Laureate



Charles M. Vest, 2006 National Medal of Technology Laureate



James E. West, 2006 National Medal of Technology Laureate

to NAE members. The medal, established by Congress in 1980, honors innovators for outstanding contributions to the nation's economic, environmental, and social well-being.

**Leslie A. Geddes**, Showalter Distinguished Professor of Bioengineering, Emeritus, Purdue University, was cited "for contributions to electrode design and tissue restoration that have led to the widespread use of numerous clinical devices. His discoveries and inventions have saved and enriched thousands of lives and have formed the cornerstone of much of the modern implantable medical device field."

**Paul G. Kaminski**, chairman and CEO, Technovation Inc., received the medal "for contributions to the

national security through the development of advanced, unconventional imaging from space, and for developing and fielding advanced systems with greatly enhanced survivability. As a result he has made a profound difference in the national security posture and the global leadership of the United States."

**Herwig Kogelnik**, adjunct photonics research vice president, Alcatel-Lucent, was honored "for pioneering contributions and leadership in the development of the technology of lasers, optoelectronics, integrated optics, and lightwave communication systems that have been instrumental in driving the tremendous capacity growth of fiber-optic transmission systems for our national communications infrastructure."

**Charles M. Vest**, NAE president and Chairman Emeritus of the Massachusetts Institute of Technology, was cited "for his visionary leadership in advancing America's technological workforce and capacity for innovation through revitalizing the national partnership among academia, government and industry."

**James E. West**, professor, Department of Electrical and Computer Engineering, Johns Hopkins University, received the medal "for co-inventing the electret microphone while working with Gerhard Sessler at Bell Labs in 1962. Ninety percent of the two billion microphones produced annually and used in everyday items such as telephones, hearing aids, camcorders, and multimedia computers employ electret technology."

## NAE Newsmakers

**Stephen Y. Chou**, Joseph C. Elgin Professor of Engineering, Princeton University, recently received a **Nano 50 Innovator Award** from *Nanotech Briefs* magazine for significant advances to the state of the art in nanotechnology. The award will be presented at a special reception and dinner during the National Nano Engineering Conference, November 14–15, at the Boston Marriott Copley Place.

**Earl H. Dowell**, William Holland Hall Professor and Dean Emeritus, Edmund T. Pratt Jr. School of Engineering, Duke University, was awarded the **2007 Walter J. and Angeline H. Crichlow Trust Prize** on April 25, 2007, at an awards luncheon during the American Institute of Aeronautics and Astronautics (AIAA) Structures, Structural Dynamics, and Materials Conference in Honolulu, Hawaii. The Crichlow Prize is awarded by AIAA every four years for excellence in aerospace materials, structural design, structural analysis, or structural dynamics. The prize includes a medal, a certificate of citation, and a \$100,000 honorarium.

**Charles Elachi**, director, Jet Propulsion Laboratory (JPL), received the **2007 International von Kármán Wings Award** from the Aerospace Historical Society. The award recognizes Dr. Elachi for “exceptional leadership at JPL, along with related distinguished technical contributions to our country and the [aerospace] industry.” Previous awardees include Professors von Kármán, Pickering, and Stone. Dr. Elachi was honored at a ceremony on May 10, 2007, at the California Institute of Technology.

At a ceremony on May 3, 2007, **Leah H. Jamieson**, Ransburg Distinguished Professor of Electrical and Computer Engineering and John A. Edwardson Dean of Engineering, Purdue University, was awarded the **2007 Women of Vision Award for Social Impact** by the Anita Borg Institute for Women and Technology. The award is given in recognition of developments or applications of technology that have had a significant impact on society.

**David C. Larbalestier**, director, Applied Superconductivity Center, National High Magnetic Field Laboratory, and Francis Eppes Professor, Department of Mechanical Engineering, Florida State University, received the **2007 Cryogenic Materials Award for Lifetime Achievements** from the International Cryogenic Materials Conference. The award was presented to Dr. Larbalestier in Chattanooga, Tennessee, on July 17, 2007.

**William J. MacKnight**, Wilmer D. Barrett Distinguished University Professor Emeritus, Department of Polymer Science and Engineering, University of Massachusetts, won the **International Award** of the Society of Plastics Engineers (SPE). Dr. MacKnight received the award on May 6, 2007, at the SPE Antec 2007 Conference in Cincinnati, Ohio. He was honored for his contributions to the understanding of structure-property relationships in ionomers, polymer blends, and polyurethanes.

**Hans Mark**, professor and John J. McKetta Centennial Energy Chair in Engineering, University of Texas, was given the **U.S. Navy’s Distinguished Public Service Award** in recognition of his more than

50 years of research “with military relevance.” Dr. Mark was recognized for his work on the development of nuclear reactors for submarines in the 1950s and tilt-rotor helicopters, which can take off like airplanes. He was also honored for leading the effort to develop electromagnetic railguns for Navy ships.

**Ronald L. Rivest**, Andres and Erna Viterbi Professor of Electrical Engineering and Computer Science at Massachusetts Institute of Technology, has been named the **2007 Marconi Fellow** and winner of the **Marconi Prize** for the creation, with two other scientists, of the most widely used public-key cryptography system and for his pioneering work in computer and network security. The award and accompanying \$100,000 prize will be presented at the annual Marconi Society Award Dinner on September 28.

**Gavriel Salvendy**, professor, School of Industrial Engineering, Purdue University, and Chair Professor and head, Department of Industrial Engineering, Tsinghua University, Beijing, China, received the **2006 John Fritz Medal** from the American Association of Engineering Societies on May 7, 2007, in Washington, D.C. Dr. Salvendy received the medal for his “fundamental, international and seminal leadership and technical contributions to human engineering and industrial engineering education, theory and practice.”

**J. Ernest Wilkins Jr.**, Distinguished Professor of Applied Mathematics and Mathematical Physics Emeritus, Clark Atlanta University, was recently honored by Chicago University for his many

achievements in math and science. A portrait of Dr. Wilkins and a plaque were unveiled in the Eckhart Hall Tea Room in the Physical Sciences Division on the university campus.

On April 27, 2007, **Wm. A. Wulf**, University Professor and AT&T Professor of Engineering and Applied Sciences, Department of Computer Science, University of Virginia, and past president of NAE, was elected a **member of the American Philosophical Society**, the oldest learned society in the United States. Founded by Benjamin Franklin in 1743, the society is dedicated to “promoting useful knowledge.”

Three NAE members became **honorary members** of the American Society of Civil Engineers (ASCE). **Zdenek P. Bazant**, McCormick School Professor and W.P. Murphy Professor of Civil Engineering and Materials Science, Northwestern University, was recognized for leadership in research and definitive contributions to structural failure and damage prediction, especially the discovery of energetic-statistical size-effect laws and their application to quasi-brittle material testing and structural design. **David E. Daniel**, president, University of Texas, was honored for his leadership in the field

of geotechnical engineering, his contributions to environmental controls for contaminated land and groundwater that have led to improvements in flood-protection systems, and his dedication to excellence in engineering education. **Jeremy Isenberg**, principal, Weidlinger Associates Inc., was recognized for his technical contributions to applications of computational mechanics to protective construction and lifeline earthquake engineering and for his leadership on risk management in ASCE and the engineering profession.

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## Message from NAE President Charles M. Vest



Charles M. Vest

The stated purpose of the National Academy of Engineering (NAE) is to promote the technological welfare of the nation by marshaling the knowledge and insights of eminent members of the engineering profession. Thus serving as NAE president is not only a great honor, but also a great responsibility, because this mission, indeed the collective mission of the National Academies, has never been more important.

NAE brings three great assets to this mission. First and foremost is our membership. Second is our

talented and dedicated staff. Third is our convening power.

Membership in NAE is a recognition of brilliant accomplishment, but more important, election to NAE is a call to serve our nation—and our world—by providing informed, objective, independent advice on technological matters.

Engineering is critical to meeting the fundamental challenges facing the U.S. economy, environment, health, security, and way of life in the 21st century. Although industries are well aware of the centrality of engineering to the production of competitive products and the delivery of services in the world marketplace, governments at both the federal and state levels are struggling to understand and incorporate scientific and technological knowledge into policies that are, literally, matters of life and death.

As NAE members, we are participants in the world's most formidable think tank. As an independent organization of nearly 2,000 of the

nation's most accomplished engineers, we can play an important role in securing our nation's future.

To support the NAE “think tank” so that it can do its work efficiently and effectively, we must continually improve the organization and work environment of our professional staff and their connectivity with our members by making better use of information and communications technology.

We also have a continuing responsibility to guarantee the independence and objectivity of our work. This is partly a matter of process—appointing boards and committees, providing exceptional professional research by our staff, and organizing and reviewing our work and reports. But it is also a matter of raising and stewarding our financial resources to support studies we believe are important, especially those studies that might not be funded by grants or contracts from government sponsors.

At the end of the day, however, the nation's well-being and leadership

in the world community depend in large measure on cutting-edge innovations based on both basic research and sophisticated development. Thus the technological welfare of the nation depends on our having a superior, innovative workforce.

Our universities and colleges continue to be world leaders in engineering learning and research, but industry, government, and universities all suffer from the consequences of our troubled K–12 system and the growing indifference of many young women and men to engineering and science. NAE can, and must, work mightily to improve this situation.

Leadership in the knowledge age will require men and women with deep engineering knowledge, vision, and the ability to participate in a system that translates innovative ideas and technologies into new products, processes, and services. Engineering leaders must be prepared to address the Herculean national challenge of remaining competitive in the emerging world economy while maintaining our standard of living.

Engineering in the 20th century was based on physics, chemistry, and electronics and was largely focused on energy, transportation, communication, and defense. Engineering in the 21st century will be based in large measure on life science and information science and should increasingly focus on the environment, sustainability, and new approaches to the generation, distribution, and conservation of energy. As we move into this exciting and demanding future, NAE, as

a member of the National Academies, can encourage synergy among science, engineering, and medicine that will lead to undreamed of discoveries and innovations.

We must inspire and educate a new generation of young men and women from diverse backgrounds to pursue careers in engineering for the purpose of improving the quality of human life and strengthening the American and worldwide economies. We must develop engineering leaders who can drive transformative technological advances and turn globalization from a threat to an opportunity.

But as a profession, we have failed miserably at communicating to young people the unparalleled opportunities for engineers to make the world better. We seem to think that communicating the excitement of engineering means telling young people why we became engineers. For instance, I could tell them how the launch of Sputnik in 1957 profoundly inspired me and influenced my career. But that was 50 years ago—ancient history to them—the equivalent of someone trying to inspire my youthful enthusiasm in 1957 by talking about the excitement of 1907!

It seems to me that young people will be excited about engineering if, and only if, engineering really is exciting. Fortunately, it is, especially at the frontiers. Indeed, this is the most exciting era for science and technology in human history. Imagine the exhilaration of working at the frontiers of the “nano/bio/

info” world—the domain of smaller and smaller, faster and faster, and more and more complex devices and systems—where science and engineering blend and disciplinary boundaries disappear. Success here will be essential to the sophisticated new products, components, and systems that will generate high-value jobs and power the U.S. economy.

Imagine the excitement of working at the frontiers of macroscopic engineering—the domain of larger and larger and more and more complex systems for energy, the environment, communications, health care, manufacturing, and logistics. Innovation and success here will be essential for meeting the daunting challenges of a world with a burgeoning population, limited resources, and justified demands for a better quality of life and more economic opportunity.

In this rapidly changing context, NAE can provide direction for policy and investment, based on careful, objective analysis, for future research and development in business, government, and engineering education. With NAE’s convening power, our ability to bring together experts, thinkers, and doers from business, academia, and government, we can provide a solid foundation for policies and practices that will address the great challenges of the 21st century.

I look forward to working with our members and staff to enhance and sustain the power of engineering, technology, and innovation in the service of our nation and a better world.

## NAE Launches Online Ethics Center

In the early 1990s, Professor Caroline Whitbeck, then a professor at Massachusetts Institute of Technology, created the Online Ethics Center (OEC) to provide engineering students, faculty, and practitioners resources for addressing ethical issues that arose with the changing technological, environmental, and sociological requirements of engineering. When she moved to Case Western Reserve University, the website moved with her. After much preparation and support from Professor Whitbeck and former NAE President **Wm. A. Wulf**, the site has now been taken over by NAE as part of its new Engineering Ethics Center (EEC).

President Wulf highlighted the importance of the ethical dimension of engineering in his keynote address in 2003 to an NAE workshop, Emerging Technologies and Ethical Issues in Engineering. "I believe the quickening pace of technological innovation, the spread of nano-

bio-, and information technology, coupled with the vastly increased complexity of systems engineers are building, raise a new class of ethical questions that the engineering profession hasn't thought about. But we need to think about them, and, in fact, the need is urgent!"

OEC (<http://www.onlineethics.org>) has two objectives: (1) to provide practicing engineers and engineering students with resources for understanding and addressing ethically significant problems; and (2) to assist educators in incorporating and promoting ethics into engineering research and practice. According to Rachelle Hollander, head of EEC and former director of the National Science Foundation (NSF) Societal Dimensions of Engineering, Science, and Technology Program, OEC "will provide engineers with a central location to explore ethical questions and share ideas."

OEC still has much of the content

it has always provided to faculty and students, practitioners, and researchers. The site is divided into six major sections: "Computers and New Technology"; "Safety and the Environment"; "Employment and Legal Issues"; "Professional Practice"; and "Responsible Research." EEC is in the process of appointing an advisory group and planning a conference series, as well as research and educational activities.

NAE member, **Raymond Stata**, president of Analog Devices, provided seed money for the OEC prototype in the early 1990s. NSF provided two grants (SBR-9511862 and SES-04285971) to support the development and operation of the site until it was transferred to NAE. **Harry E. Bovay Jr.**, president of MidSouth Telecommunications Company and an NAE member, has contributed funds for the transition and ongoing support for the site, as well as for the new EEC.

## Quality-of-Life Technology, an NAE Regional Meeting at Carnegie Mellon University

Quality-of-life technology is an emerging research area that combines robotics, computer science, rehabilitation engineering, bioengineering, and a number of clinical specialties, social sciences, and public policy to address the needs of older adults and people with disabilities. The objective of this regional NAE meeting was to profile needs, opportunities, and ongoing research that underscore the direct impact of engineering on people's lives and to

highlight an area in which engineering addresses social issues responsibly and compassionately.

Introductory remarks were made by host **Randal Bryant**, dean and University Professor, School of Computer Science, Carnegie Mellon University; former NAE President **Wm. A. Wulf**; and **Savio Woo**, Whiteford Professor and director, Musculoskeletal Research Center, Department of Bioengineering, University of Pittsburgh. Invited

speakers described quality-of-life problems and technological solutions being developed to address them.

Michael McCue, a clinical psychologist at the University of Pittsburgh, identified challenges facing people with disabilities in their everyday lives and work and underscored the magnitude and implications of those issues to society as a whole. He focused on cognitive disabilities, which affect people of all ages, and current research in

technology to enable people with traumatic brain injuries to attain and maintain job skills.

Neil Resnick, chief of geriatric medicine at the University of Pittsburgh Medical Center, described the myriad health issues faced by older adults and described advances in technology that can lead to better management of chronic diseases. He emphasized the potential benefits of practical, yet innovative, approaches that are realizable in the near term.

The next talk was delivered by John Bertoty, executive director of Blueroof Technologies, a local nonprofit organization that is developing affordable, accessible, energy-efficient housing that enables older adults and people with disabilities to live securely and independently. “Smart” Blueroof houses feature cleverly integrated sensors, home automation, and health-monitoring

technologies. University students and “senior research associates” (local senior citizens) assist in the design and evaluation of Blueroof smart homes.

Rory Cooper, co-director of the newly established Quality of Life Technology Center, an NSF Engineering Research Center operated jointly by Carnegie Mellon and the University of Pittsburgh, gave the final presentation. He outlined the center’s 10-year research agenda, which includes cognitive aids, mobility and manipulation technologies, driving aids to enable older adults to operate personal vehicles confidently and safely, and robotics that can turn smart homes into active homes. He also highlighted the need for interdisciplinary teams and the direct involvement of end-users in research and development.

The symposium included an exposition showcasing work being done

in the Quality of Life Center and related projects by students from both universities. Poster presentations included research on perception and data-mining to measure, analyze, and categorize human activities and behaviors; customizing and simplifying interfaces for powering wheelchairs and computers; electronic job coaches; applications of information technology in disease management; smart wheelchairs; and focus group studies on robotic aids for stowing and retrieving wheelchairs in passenger vehicles. There were also hands-on demonstrations of active seating technologies and computer games for rehabilitation.

The 75 attendees at the meeting included NAE members, interested individuals from the general public and the university community, and representatives of local nursing homes, nonprofit support and advocacy groups, and end-users.

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## International Colloquium on Women in Engineering and Technology



Johanna Levelt Sengers, Naadiya Moosajee, cofounder of South African Women in Engineering (SAWomEng), and Sarah Kiggundu, events coordinator, SAWomEng.

The World Federation of Engineering Organizations (WFEO) held an international meeting on women and engineering in Tunis,

Tunisia, June 6–8, 2007. WFEO, a nongovernmental organization of engineering associations, represents 15 million engineers from more

than 90 nations. This was the first time in the organization’s 40-year history that an event was focused on women and engineering. The colloquium explored issues in engineering education, the workforce, entrepreneurship, and enabling technology for communities.

More than 400 participants from 60 countries attended, as well as representatives of national engineering societies (e.g., U.S. Society of Women Engineers, Australian Institute of Engineers, and French Society of Women Engineers), UNESCO, the World Bank, and the United Nations Development Program. The plenary sessions were in Arabic, French, and English with simultaneous translation. In

conjunction with the colloquium, a two-day training event for young women engineers was held on developing leadership, entrepreneurial, and networking skills.

**Johanna Levelt Sengers**, an NAE member, delivered the keynote address on the first morning on how engineering organizations can encourage and facilitate the careers of women in engineering. Sengers cited one company, Schlumberger,

that set a goal of having 25 percent female engineers within 15 years. The company achieved its goal last year, ahead of schedule.

The colloquium concluded with participants endorsing the “Carthage Declaration on Empowering Women in Engineering and Technology,” which calls for the creation of a WFEO standing committee on women in engineering and for WFEO to work with member organi-

zations to create a network to address issues relevant to women in engineering. The Carthage Declaration and presentations at the colloquium are available online at [http://www.wfeo.org/documents/download/declaration\\_eng.pdf](http://www.wfeo.org/documents/download/declaration_eng.pdf) and <http://www.wfeo.org/women/program.html>. Catherine Didion, NAE senior program officer, Diversity of the Engineering Workforce Program, attended the conference.

## Research on Engineering Education at Historically Black Colleges and Universities and Hispanic-Serving Institutions

For the past three years, the NAE Center for the Advancement of Scholarship on Engineering Education (CASEE) has been working with the Council of Engineering School Deans of Historically Black Colleges and Universities (HBCUs) and with deans of Hispanic-serving institutions (HSIs) with high engineering enrollment to improve their capacity for rigorous research on engineering education. Three-person teams from 11 HBCUs and two-person teams from 12 HSIs have attended workshops

held by CASEE on conducting engineering education research, institutional transformation in engineering and science, and emerging practices in research on engineering education.

Summaries of the experiences and reactions of engineering deans and faculty members, and a survey of participants, have revealed some common reactions: (1) improved understanding of issues in engineering education research and an appreciation of the potential benefits of incorporating scholarly research into the engineering

curriculum; (2) increased opportunities for collaborating with other engineering education researchers; (3) participation in engineering-education research by several individual faculty members and some entire departments; (4) new information that has been incorporated into classroom courses; and (5) increased collaboration between participants and their colleagues at the same or other institutions.

This project is supported by the National Science Foundation under grant DUE-0411994.

## Women’s Equality Day



Catherine Didion

Catherine Didion, senior program officer at NAE, was the invited guest speaker on August 3, 2007, at the National Science Foundation (NSF) 2007 commemoration of Women’s Equality Day. **Arden Bement**, director of NSF, presided over the event and gave the welcoming remarks. Didion’s talk, “Pathways to Equality and Excellence,” focused on recent findings about how high-school women view engineering and what the engineering community can do to encourage

all students to pursue undergraduate degrees in science and engineering.

Didion provided an overview of NAE’s current efforts to raise public awareness of the importance and excitement of engineering careers and to ensure diversity in the engineering workforce. She also highlighted several NAE publications and websites that have been developed as resources for the engineering community and for students, parents, and educators.

## Summer Intern and Fellows Join NAE Program Office



Priscilla Arriaga

Priscilla Arriaga has completed one year of study at Montgomery College-Rockville, where she is majoring in chemical engineering. This summer, in preparation for her second year, she took a course in calculus. When she graduates, she plans to continue working toward a bachelor's degree at a four-year institution and, perhaps, go on to obtain a master's degree in biochemical engineering.

A second-year Anderson-Commonweal Intern at the National Academies, Priscilla worked in the NAE Program Office this summer. Her time was devoted to updating the NAE website, helping with preparations for a meeting of the Committee on Developing Effective Messages for Improving Public Understanding of Engineering, and assisting in activities related to engineering programs in community colleges. When time permits, she enjoys spending time with her sister and younger brother, as well as writing and reading.

Patrick Cunningham, a Christine Mirzayan Science and Technology Policy Fellow, completed his Ph.D. in mechanical engineering at Purdue University in the fall of 2006. His doctoral research on monitoring diesel particulate filters was focused on experimental and theoretical



Patrick Cunningham

correlations between dynamic pressure signal features and the amount of diesel particulate stored in a filter. His graduate work was partly funded by an NSF fellowship. Patrick also received his M.S.M.E. and B.S.M.E. from Purdue University.

Since November 2006, Patrick has been following his passion for teaching at Rose-Hulman Institute of Technology as an assistant professor in the Mechanical Engineering Department. He is particularly interested in how engineers are taught to balance the often-competing social, cultural, political, economic, and environmental requirements of engineering projects. His career goals include inspiring and challenging future mechanical engineers, improving the ethical and social acuity of students and the pedagogy behind it, and conducting research promoting efficient energy conversion and reduced vehicle emissions. As a fellow at the NAE Center for the Advancement of Scholarship on Engineering Education (CASEE), he worked on assessments of instructional practices.

Susan Su, another Christine Mirzayan Science and Technology Policy Fellow, graduated from the University of California, San Diego, with a Ph.D.



Susan Su

in bioengineering in January 2007. Her graduate research on the mechanotransducing behavior of human leukocytes in the context of inflammation focused on using numerical methods to characterize the membrane stress of leukocytes under blood flow and record the translocation of membrane molecules caused by fluid shear. Susan graduated magna cum laude from Binghamton University with a B.S. in mechanical engineering and a minor in Spanish. During her graduate years, she spent several hours every weekend as a volunteer at the Birch Aquarium at the Scripps Institution of Oceanography.

Susan's work with the NAE Diversity of the Engineering Workforce Program included composing the content of a new website encouraging young women to pursue careers in engineering and compiling published findings on women in engineering and science occupations. She also worked with other fellows to organize a seminar on a controversial topic in science-related government regulations. Eventually, Susan hopes to work in international science policy, particularly to promote U.S.-China science collaborations. In her spare time, she enjoys indoor rock climbing, Argentine tango, day tripping, and traveling, when time and finances permit.

## Calendar of Meetings and Events

September 20	Gordon Prize Committee Final Meeting	October 9–10	Dane and Mary Louise Miller Symposium and CASEE Annual Meeting Milwaukee, Wisconsin	November 13	NRC Governing Board Executive Committee Meeting
September 24–26	Frontiers of Engineering Symposium Redmond, Washington	October 17	NRC Governing Board Executive Committee Meeting	November 13–14	NRC Governing Board Meeting
September 28	Finance and Budget Committee Meeting	October 22–23	K–12 Engineering Education Workshop and Committee Meeting	November 14–16	Keck Futures Initiative: The Future of Human Healthspan Irvine, California
September 28–29	NAE Council Meeting	October 23–26	Convocation of the International Council of Academies of Engineering and Technological Sciences (CAETS) Tokyo, Japan	December 7–8	NAE Committee on Membership Meeting Irvine, California
September 29	NAE Peer Committee Meeting	November 5–7	Japan-America Frontiers of Engineering Symposium Palo Alto, California	December 13	NRC Governing Board Executive Committee Meeting
September 30–October 1	NAE Annual Meeting				
October 2	Draper Prize Committee Final Meeting				
October 8	CASEE Advisory Committee Meeting Milwaukee, Wisconsin				

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

## In Memoriam

**M. ROBERT AARON**, 84, retired consultant, died June 16, 2007. Mr. Aaron was elected to NAE in 1979 “for contributions to design tools and systems concepts essential for the realization of digital communications on the telephone network.”

**JACKSON L. DURKEE**, 84, consulting structural engineer, died June 14, 2007. Mr. Durkee was elected to NAE in 1995 “for origination and development of innovations in fabrication and erection engineering of long-span bridges.”

**MICHAEL FIELD**, 93, retired chairman and CEO, Metcut Research Associates Inc., died May 26, 2007. Dr. Field was elected to NAE in 1976 “for discoveries and developments in the fields of machine tool engineering, machining, and surface integrity.”

**CHARLES D. GRESKOVICH**, 65, consultant, CDG Ceramic Solutions, died July 7, 2007. Dr. Greskovich was elected to NAE in 2000 “for innovations in technical ceramics and their manufacturing processes.”

**WILLIAM J. LEMESSURIER**, 81, Chairman Emeritus, LeMessurier Consultants Inc., died June 14, 2007. Mr. LeMessurier was elected to NAE in 1978 “for teaching, research, and practice of structural design for buildings, with special concern for the relationship of structures to total architecture.”

**TUNG-HUA LIN**, 96, Professor Emeritus, Department of Civil Engineering, University of California, Los Angeles, died June 25, 2007. Dr. Lin was elected to NAE in 1990 “for pioneering development of micro-mechanical theories of plasticity, creep, and fatigue crack initiation

and major contributions to inelastic structure analysis.”

**THEODORE H. MAIMAN**, 79, independent consultant, died May 5, 2007. Dr. Maiman was elected to NAE in 1967 “for the design and constructing of lasers.”

**JOSEPH MILLER**, 70, retired vice president and general manager, Applied Technology Division, TRW Space and Electronics Group, died July 5, 2007. Dr. Miller was elected to NAE in 1991 “for contributions to advanced high-power lasers and optical systems.”

**JOHN R. MOORE**, 91, consultant to high-technology enterprises, died July 13, 2007. Mr. Moore was elected to NAE in 1978 “for contributions in the theory, conception, design, and manufacture of navigation, guidance, and control equipment.”

# Publications of Interest

The following reports have been published recently by the National Academy of Engineering or the National Research Council, unless otherwise noted. National Academies publications are for sale (prepaid) from the National Academies Press (NAP), 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055. For more information or to place an order, contact NAP online at <http://www.nap.edu> or by phone at (888) 624-8373. (Note: Prices quoted are subject to change without notice. Online orders receive a 20 percent discount. Please add \$4.50 for shipping and handling for the first book and \$0.95 for each additional book. Add applicable sales tax or GST if you live in CA, DC, FL, MD, MO, TX, or Canada.)

**Beyond Bias and Barriers: Fulfilling the Potential of Women in Academic Science and Engineering.** Because female scientists and engineers face barriers to success in every field, the country continues to be deprived of an important source of talent. Unless there is a transformation in academic institutions to bring down such barriers, the future vitality of the U.S. research base and economy may be in jeopardy. Eliminating gender bias in academia will require basic reforms by university administrators, professional societies, federal funding agencies and foundations, government agencies, and Congress. If implemented and coordinated across public, private, and government sectors, the actions recommended in this report will improve workplace environments for all employees and

reinforce the foundation of American competitiveness.

NAE members **Alice M. Agogino**, Roscoe and Elizabeth Hughes Professor of Mechanical Engineering, University of California at Berkeley, and **Elaine Weyuker**, AT&T Fellow, AT&T Labs Research, were members of the study committee. Hardcover, \$50.95.

**River Science at the U.S. Geological Survey.** Rivers provide about 60 percent of the drinking water and irrigation water and 10 percent of the nation's electric power needs. These sometimes-incompatible demands on rivers often lead to policy and management conflicts that can only be resolved with science-based information. This report provides advice to the U.S. Geological Survey (USGS) on using its resources effectively and coordinating its activities with other agencies. The report identifies the highest priority river-science issues, including environmental flows and river restoration, sediment transport and geomorphology, and groundwater-surface water interactions. Two cross-cutting science activities are recommended: (1) the surveying and mapping of all river systems according to key physical and landscape features; and (2) a more intense focus on predictive models, especially models that simulate interactions between physical and biological processes. Key variables to be monitored and data-managed are also identified. Improvements are recommended in the monitoring of streamflows, biological conditions, and sediment

transport and buildup, which will require the establishment of multi-disciplinary, integrated monitoring sites and a comprehensive sediment monitoring program. Finally, USGS is encouraged to take the lead in new technology applications, such as using airborne lidar and embedded, networked, wireless sensors.

NAE member **Gerald E. Galloway Jr.**, Glenn L. Martin Institute Professor of Engineering, University of Maryland, College Park, was a member of the study committee. Paper, \$42.75.

**Agricultural Water Management: Proceedings of a Workshop in Tunisia.** This report contains a collection of papers from a workshop, Strengthening Science-Based Decision-Making for Sustainable Management of Scarce Water Resources for Agricultural Production, held in Tunisia. Participants from the United States and several countries in North Africa and the Middle East included scientists, decision makers, representatives of nonprofit organizations, and one farmer. The papers examine constraints on agricultural production from a scarcity of water focusing on (1) the state of the science regarding water management for agricultural purposes in the Middle East and North Africa and (2) how science can be applied to improve the management of existing water supplies and optimize the domestic production of food and fiber. The cross-cutting themes of the workshop included principles of science-based decision making, how the scientific community can

ensure that science is an integral part of decision making, and how communications between scientists and decision makers can be improved.

NAE member **Perry L. McCarty**, Silas H. Palmer Professor Emeritus, Stanford University, was a member of the workshop steering committee. Paper, \$34.50.

**Review of the Worker and Public Health Activities Program Administered by the Department of Energy and the Department of Health and Human Services.**

Ever since the United States began producing and testing nuclear weapons during World War II, serious concerns have been raised about the effects of ionizing radiation on human health and the environment. The Worker and Public Health Activities Program was established more than 20 years ago to study the consequences of exposure of workers and people in surrounding communities to ionizing radiation and other hazardous materials from U.S. Department of Energy (DOE) operations. This report concludes that the program has used sound research methods and has generally improved the public understanding of the risks. However, the report recommends increased two-way communication between government agencies, workers, and the public. The report includes a discussion of how the agencies involved could develop a more coordinated, effective, and thorough evaluation of public health concerns related to the cleanup and remediation of DOE sites.

NAE member **Edwin P. Przybyłowicz**, retired senior vice president, Eastman Kodak Company, chaired the study committee. Paper, \$57.50.

**Improving Disaster Management: The Role of IT in Mitigation, Preparedness, Response, and Recovery.**

Information technology (IT) can be critical in managing natural and human-made disasters. Response and recovery efforts following Hurricane Katrina were hampered by damage to communications infrastructure and other communications problems. To assist government planning in this area, in the E-government Act of 2002, Congress directed the Federal Emergency Management Agency (FEMA) to request that the National Research Council conduct a study on using IT in disaster management. This report characterizes disaster management and provides a framework for determining the range and nature of information and communication needs; discusses the potential for IT to improve disaster management; provides an analysis of structural, organizational, and other nontechnical barriers to the acquisition, adoption, and effective use of IT during and after disasters; and outlines a research program that would improve IT-enabled capabilities for disaster management.

NAE member **Masanobu Shinozuka**, UCT Distinguished Professor and chairman, Department of Civil and Environmental Engineering, University of California, Irvine, was a member of the study committee. Paper, \$40.25.

**A Performance Assessment of NASA's Astrophysics Program.**

Continuing the dramatic progress in astronomy and astrophysics of the last 20 years will require leadership from NASA. To determine if NASA can meet this challenge, in the 2005 NASA Authorization Act, Congress directed the agency to have "[t]he performance of each division in the

Science Directorate . . . reviewed and assessed by the National Academy of Sciences at 5-year intervals." In early 2006, NASA asked the National Research Council (NRC) to conduct an assessment of the Astrophysics Division. This report provides a detailed analysis of how well NASA's current program addresses the strategies, goals, and priorities outlined in previous NRC reports. The study also suggests actions that could be taken to optimize the scientific value of the program in the context of current and forecasted resources.

NAE member **Kenneth H. Keller**, director and professor, Johns Hopkins School of Advanced International Studies, Bologna, Italy, chaired the study committee. Paper, \$18.00.

**Colorado River Basin Water Management: Evaluating and Adjusting to Hydroclimatic Variability.**

Studies of climate and streamflow conditions for the past 100 years have revealed that several times in recent years streamflow has reached record low levels. Considering the rapid growth of urban populations in the West and significant climate warming in the region, water managers must prepare for possible reductions in water supplies that cannot be averted by traditional means. This National Research Council report assesses existing scientific information, including temperature and streamflow records, tree-ring based reconstructions, and climate-model projections, and how that information relates to Colorado River water supplies and demands, water management, and drought preparedness. The report concludes that successful adjustments to new conditions will entail sustained cooperation among

the seven states in the Colorado River basin and recommends that a comprehensive, basin-wide study be conducted of urban water practices to improve planning for future droughts and water shortages.

NAE member **Ernest T. Smerdon**, Dean of Engineering Emeritus, University of Arizona, chaired the study committee, and NAE member **Eugene M. Rasmusson**, Research Professor Emeritus, Department of Atmospheric and Ocean Science, University of Maryland, was a member of the study committee. Hardcover, \$45.25.

**Strategic Guidance for the National Science Foundation's Support of the Atmospheric Sciences.**

The National Science Foundation's Division of Atmospheric Sciences (ATM) supports research to develop a better understanding of Earth's atmosphere and how the Sun impacts it. This report provides guidance to ATM on its strategy for achieving its goals in the atmospheric sciences, including cutting-edge research, education and workforce development, service to society, computational and observational objectives, and data management. The report reviews how the atmospheric sciences have evolved over the past several decades and analyzes the strengths and limitations of various modes of support. The study committee concludes that ATM is operating in an increasingly cross-disciplinary, inter-agency, and international environment that requires a more strategic approach to encourage the active participation of the atmospheric sciences community. At the same time, ATM should preserve opportunities for basic research, especially high-risk, potentially transformative, projects that are unlikely to

be supported by other government agencies. Finally, ATM should be more proactive in attracting highly talented students to the atmospheric sciences as an investment in future breakthroughs.

NAE members on the study committee were **John A. Armstrong**, retired vice president for science and technology, IBM Corporation (committee chair), and **Margaret A. LeMone**, senior scientist, National Center for Atmospheric Research. Paper, \$44.25.

**Distributed Remote Sensing for Naval Undersea Warfare: Abbreviated Version.**

The widespread availability of quiet, diesel-electric submarines and inexpensive mines poses a growing threat to global access by the U.S. Navy. In response to that threat, the Navy has expanded its work on undersea warfare (USW) with an emphasis on the potential for new, distributed remote sensing (DRS) approaches. To assist with this effort, the former Chief of Naval Operations requested that the National Research Council conduct an assessment of DRS for naval USW. This report describes a clear, near-term path by which useful DRS systems can be applied rapidly to pressing naval USW problems and by which ongoing science and technology efforts can be directed toward the most useful options. Because the full report contains information described in 5 U.S.C. 552(b) and could not be released to the public in its entirety, the committee prepared this public version, which consists of the front matter and executive summary from the report.

NAE member **Arthur B. Baggeroer**, Ford Professor of Engineering, Secretary of the Navy/Chief of Naval Operations, and Chair in

Oceanographic Science, Massachusetts Institute of Technology, co-chaired the study committee. NAE member **L. David Montague**, president, L. David Montague Associates, and retired president, Missile Systems Division, Lockheed Martin Missiles & Space, was a member of the study committee. Paper, \$12.00.

**The Role of Naval Forces in the Global War on Terror: Abbreviated Version.**

The growing threat of terrorism has created significant strategic challenges for U.S. armed forces in the global war on terror (GWOT). For the Navy, the challenges have centered on the development of maritime capabilities to prosecute GWOT as far forward as possible. The former Chief of Naval Operations requested that the National Research Council conduct an assessment of the adequacy of and prospects for improving the role of naval forces in the GWOT. The full study, which developed a defense-in-depth framework as the organizing principle for the report, contains information described in 5 U.S.C. 552(b) and therefore could not be released to the public in its entirety. The public version consists of an executive summary that includes an assessment of the transformation of naval forces for addressing the GWOT; a brief description of the defense-in-depth framework; and a list of findings and major recommendations.

NAE members **H. Norman Abramson**, retired executive vice president, Southwest Research Institute, and **David A. Whelan**, vice president strategic growth, The Boeing Company, were members of the study committee. Paper, \$12.00.

### **U.S.-Russian Collaboration in Combating Radiological Terrorism.**

The International Atomic Energy Agency reports numerous incidents of illicit trafficking in radioactive materials, including ionizing radiation sources (IRSs) used in medical, agricultural, and industrial applications. This report assesses the threats posed by inadequately protected IRSs in Russia and recommends steps for making the U.S. Department of Energy's (DOE's) current cooperative program with Russia more effective. The report recommends a current program of quick security fixes and the development of a comprehensive plan to work with Russian counterparts to reduce overall risk, within the context of a comprehensive Russian program for ensuring adequate life-cycle management of IRSs.

NAE member **John F. Ahearne**, director, Ethics Program, Sigma Xi, The Scientific Research Society, chaired the study committee, and NAE member **Siegfried S. Hecker**, Visiting Professor, CISAC, Stanford University, was a member of the study committee. Paper, \$28.75.

### **Improving the Nation's Water Security: Opportunities for Research.**

Concerns about terrorist attacks since 2001 have directed attention to potential vulnerabilities in the nation's water and wastewater systems. The Environmental Protection Agency (EPA), which leads federal efforts to protect the water sector, initiated a research program in 2002 to address immediate research and technical-support needs. This report, conducted at EPA's request, evaluates progress and provides a long-term vision for EPA's research program. The report recommends that EPA develop a strategic research plan,

address gaps in expertise among EPA program managers and researchers, and improve the way information is disseminated. The report recommends several high-priority research topics for EPA, including empirical research in behavioral science to determine the best way to prepare people for water-security incidents.

NAE members on the study committee were **Henry G. Schwartz Jr.**, consultant, St. Louis, Missouri, and **George Tchobanoglous**, Professor Emeritus, University of California, Davis. Paper, \$36.50.

### **Innovation Policies for the 21st Century: Report of a Symposium.**

To mark the opening of a study of Comparative Innovation Policy: Best Practices for the 21st Century, the Board on Science, Technology, and Economic Policy (STEP) convened a symposium to provide an overview of areas to be examined in the study and topics that require further attention. The event highlighted the policies and programs of leading nations and provided valuable insights into some of the common challenges of growing and supporting high-technology industry and the commercialization of public investments in R&D. This volume provides a summary of the symposium proceedings and an introductory analysis of the issues in a broad policy context.

NAE members on the study committee were **William J. Spencer**, Chairman Emeritus, SEMATECH, (committee chair); **Mary L. Good**, Donaghey University Professor and dean, Donaghey College of Information Science & Systems Engineering, University of Arkansas at Little Rock, and former under secretary for technology, U.S. Department of Commerce (committee co-vice chair); and **Lewis S. Edelheit**, retired

senior vice president, GE Corporate Research and Development. Hardcover, \$45.25.

### **Engaging Privacy and Information Technology in a Digital Age.**

With the spread of the Internet and seemingly boundless options for collecting, saving, sharing, and comparing information, protecting privacy is a growing concern in the United States and around the world. Online practices by business and government agencies may present new ways of compromising privacy, and e-commerce and technologies that make a wide range of personal information available to anyone with a Web browser only hint at the possibilities for inappropriate or unwarranted intrusions into our personal lives. This report presents a comprehensive, multidisciplinary examination of privacy in the information age. It addresses how threats to privacy evolve, how privacy can be protected, and how society can balance the interests of individuals, businesses, and government in ways that promote privacy reasonably and effectively. The purpose of the report is to raise awareness of the interaction of individual actions and privacy policies and to suggest tools and concepts to encourage discussions about privacy. The study focuses on (1) technological change, (2) societal shifts, and (3) circumstantial discontinuities.

NAE member **Ronald L. Rivest**, professor of computer science, Massachusetts Institute of Technology, was a member of the study committee. Hardcover, \$49.95.

### **International Benchmarking of U.S. Chemical Engineering Research Competitiveness.**

Innovations in chemistry are crucial to more than \$400 bil-

lion worth of products. Chemical engineering, as an academic discipline and as a profession, has enabled this achievement. In response to growing concerns about the future of the discipline, the National Science Foundation asked the National Research Council to conduct an in-depth benchmarking analysis to gauge the standing of the U.S. chemical engineering enterprise in the world, based on measures such as the numbers of published papers, citations, trends in the awarding of degrees, patent productivity, and awards. The analysis showed that the U.S. publishes more papers than any other nation and that 73 of the 100 most cited papers in the chemical engineering literature from 2000 to 2006 originated in the United States. The report concludes that the United States is now, and is expected to remain, a world leader in all subareas of chemical engineering research, especially biocatalysis and protein engineering; cellular and metabolic engineering; systems, computational, and synthetic biology; nanostructured materials; fossil energy extraction and processing; non-fossil energy; and green engineering. However, U.S. leadership in some classical and emerging subareas will be strongly challenged. For example, Japan and other Asian countries are particularly competitive in materials-oriented research, and Europe is very competitive in bio-related research.

NAE member **George Stephanopoulos**, A.D. Little Professor of Chemical Engineering, Massachusetts Institute of Technology, chaired the study committee. Other NAE members on the study committee were **William F. Banholzer**, corporate vice president and chief technology officer, Dow Chemical

Company; **L. Louis Hegedus**, retired senior vice president, Research and Development, Arkema Inc.; **Julio M. Ottino**, R.R. McCormick Institute Professor, Walter P. Murphy Professor of Chemical & Biological Engineering, and dean, R.R. McCormick School of Engineering and Applied Science, Northwestern University; **Nicholas A. Peppas**, Fletcher Stuckey Pratt Chair in Engineering, University of Texas at Austin; **Julia M. Phillips**, director, Physical, Chemical, and Nano Sciences Center, Sandia National Laboratories; and **Adel F. Sarofim**, Presidential Professor, Department of Chemical Engineering, University of Utah. Paper, \$54.00.

**50 Years in Nuclear Power: A Retrospective.** This new book describes significant events in a half-century of nuclear-power generation. The history of the first 25 years deals with the development, design, safety, manufacturing, licensing, and operations of light-water reactors, particularly General Electric boiling-water reactors. During those years the public perceptions about nuclear power changed, and orders for new nuclear power plants came to a halt. The history of the subsequent 25 years covers the formation and operation of S. Levy Incorporated, an engineering/management firm that provided consulting services to the entire nuclear industry.

The author **Salomon Levy**, owner, Levy & Associates, is an NAE member. Hardcover, 252 pages, \$35.00. Available from the American Nuclear Society, Chicago, Illinois.

**Assessment of the Results of External Independent Reviews for U.S. Department of Energy Projects.** External independent reviews (EIRs) and

independent project reviews are essential to the U.S. Department of Energy's (DOE's) project management. These reviews were established as part of the critical decision process for project management set forth in DOE Order 413.3 issued in 2000. In addition, Congress continues to support the use of EIRs to validate project performance baselines. For EIRs to be most effective in a time of growing budget pressure, DOE must ensure that they are effectively planned, efficiently executed, and provide added value to each project. To assist in meeting these goals, DOE asked the National Research Council for advice on how EIRs can be tailored to ensure that essential information is provided at the optimum point in the critical decision process; that resources are focused on the riskiest projects; and that EIRs are cost effective. This report presents a review of characteristics of effective EIRs, an assessment of criteria for structuring review programs, and recommendations for improving the EIR process.

NAE member **Joseph P. Colaco**, president, CBM Engineers Inc., chaired the study committee. Paper, \$18.00.

#### **Review of NASA's Space Flight Health Standards-Setting Process: Letter Report.**

At the request of the National Aeronautics and Space Administration (NASA), the Institute of Medicine (IOM) established a committee to examine the process by which NASA establishes space-flight health standards for human performance. The committee concluded that the initial standards-setting process developed by NASA is carefully designed, evidence-based, and includes input from relevant

stakeholders; the process follows an occupational health model as recommended in several prior IOM reports; and the analytical framework can make human space flight safer. The committee recommended the following improvements: increasing the opportunities for input and review; strengthening the evidence review; increasing research and validation efforts; improving updates, appeals, and the development of new standards; and using an integrated systems approach.

NAE member **Van C. Mow**, Stanley Dicker Professor of Biomedical Engineering and chair, Department of Biomedical Engineering, Columbia University, was a member of the study committee. Free PDF.

#### **Implementing the Stockholm Convention on Persistent Organic Pollutants: Summary of a Workshop in China.**

This report provides a summary of a workshop held June 7–10, 2004, in Beijing, China. The presentations and discussions summarized in this volume describe the types of scientific information necessary to inform decisions for eliminating the production and use of persistent organic pollutants (POPs) that are banned under the Stockholm Convention; sources of information; scientifically informed strategies for eliminating POPs; elements of good scientific advice, such as transparency, peer review, and disclosure of conflicts of interest; and next steps for making such scientific information available to decision makers on a continuing basis.

NAE member **Perry L. McCarty**, Silas H. Palmer Professor Emeritus, Stanford University, was a member of the workshop steering committee. Paper, \$12.00.

#### **A Path to the Next Generation of U.S. Banknotes: Keeping Them Real.**

Rapid advances in digital printing pose serious challenges to the U.S. Department of the Treasury's Bureau of Engraving and Printing (BEP), which is trying to stay ahead of the evolving threat of counterfeiting of U.S. currency. To help BEP meet those challenges, the National Research Council was asked to assess methods of producing designs that would increase the security of U.S. Federal Reserve notes (FRNs). This report presents the results of a systematic investigation of trends in digital imaging and printing that have increased the threat of counterfeiting; the identification and analysis of features of FRNs that could effectively counter those threats; and an overview of a requirements-driven development process that could be adapted for next-generation currency.

NAE members on the study committee were **Charles B. Duke**, retired vice president and senior research fellow, Xerox Corporation; **Pradeep K. Khosla**, dean, College of Engineering, Carnegie Mellon University; **Stephen M. Pollock**, Herrick Emeritus Professor of Manufacturing, University of Michigan; and **Gary K. Starkweather**, retired architect, Microsoft Corporation. Paper, \$57.00.

#### **Improving the Efficiency of Engines for Large Nonfighter Aircraft.**

Faced with rapidly increasing fuel costs and our growing dependency on imported oil, the U.S. Air Force asked the National Research Council to assess technical options for improving the engine efficiency of all large nonfighter aircraft under Air Force command. This report presents a review of current Air Force fuel

consumption patterns; an analysis of previous programs for replacing aircraft engines; an examination of proposed engine modifications; an assessment of the potential impact of alternative fuels and engine science and technology programs; and an analysis of costs and funding requirements.

NAE member **Natalie W. Crawford**, senior fellow, RAND Corporation, was vice chair of the study committee. Other NAE members on the study committee were **Meyer J. Benzakein**, chair, Aerospace Engineering Department, Ohio State University; **David E. Crow**, professor of mechanical engineering, University of Connecticut, and retired senior vice president of engineering, Pratt and Whitney; **Alan H. Epstein**, R.C. Maclaurin Professor, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology; **Neil E. Paton**, chief technology officer, Liquidmetal Technologies; and **Eli Reshotko**, Kent H. Smith Professor Emeritus of Engineering, Case Western Reserve University. Paper, \$40.25.

#### **Models in Environmental Regulatory Decision Making.**

Many regulations issued by the U.S. Environmental Protection Agency (EPA) are based on the results of computer models, which can enable EPA to investigate environmental phenomena in settings where direct observations are limited or unavailable and anticipate the effects of agency policies on the environment, human health, and the economy. Given the importance of models, EPA asked the National Research Council to assess scientific issues related to the agency's selection and use of models. The report recommends

guidelines and principles for improving agency models and decision-making processes. The centerpiece of the recommendations is a life-cycle approach to evaluating models that includes peer review, corroboration of results, and other activities.

NAE member **Chris G. Whipple**, principal, ENVIRON, chaired the study committee. Paper, \$56.25.

**India's Changing Innovation System: Achievements, Challenges, and Opportunities for Cooperation: Report of a Symposium.** For a study of comparative innovation policies, the Board on

Science, Technology, and Economic Policy convened a symposium in 2006 to examine policy changes that have contributed to India's innovative capacity. The symposium brought together leaders from the public and private sectors in India and the United States to identify accomplishments and remaining challenges in the Indian innovation system and review opportunities for cooperation between the two countries. This report provides an introductory analysis of the policy issues raised at the symposium, a research paper on India's knowledge economy, and a summary of symposium presentations.

NAE members on the study committee were **William J. Spencer**, Chairman Emeritus, SEMATECH, (committee chair); **Mary L. Good**, Donaghey University Professor and dean, Donaghey College of Information Science & Systems Engineering, University of Arkansas at Little Rock, and former under secretary for technology, U.S. Department of Commerce (committee co-vice chair); and **Lewis S. Edelheit**, retired senior vice president, GE Corporate Research and Development. Hardcover, \$45.75.



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