Spring 2007

The BRIDGE

LINKING ENGINEERING AND SOCIETY

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Yossi Sheffi

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Erratum

In "The Changing Face of Engineering Education" (pp. 5–13) in the summer 2006 issue, the line at the bottom of Figures 4, 5, and 6 should read "5 point scale, where 1 = no ability and 5 = high ability."

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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Editor's Note

William H. Hooke is director of the Policy Program, American Meteorological Society.

Engineering for the Threat of Natural Disasters

Engineers are in the business of improving public health and safety, facilitating economic growth, protecting the environment and ecosystems, and providing for national security. And, they attempt to accomplish all of this on a planet that does its business through extreme events. The earthquakes we experience are crustal manifestations of Earth's continental drift. "Climate" is really the aggregate of patterns and statistics of extremes of heat and cold, flood and drought. What we call climate variability, or climate change, is really a change in those patterns.

Disasters occur at the intersection between natural extremes and human populations and the built environment. Thus they are social constructs, not the results of natural hazards alone. Disasters are about centuries of decisions—especially about where and how to build—with an overlay of cultural and ethnic preferences, demographics, and economic decisions for developing and allocating wealth. Thus they are not solely a matter of emergency response.

NAE recently sponsored a symposium on engineering for the threat of natural disasters. Engineering for the threat of natural disasters is a broad topic, and the papers in this issue cannot possibly do the topic full justice. However, they can stimulate discussion and ideas for the future. The first three articles, which are based on presentations given at the symposium, draw lessons from three recent natural disasters: Hurricane Katrina (by John Christian), the Indian Ocean tsunami in 2004 (by Lloyd Cluff), and the earthquake in Pakistan in 2005 (by Melvyn Green).

In John Christian's review of engineering studies related to Katrina, he describes several plausible explanations for levee failures in New Orleans. He concludes that a number of mechanisms were at work and that it is impossible to place the blame on any one of them. He calls for better engineering in the future, external peer reviews of both designs and construction, and more rigorous analysis of what went wrong with the evacuations.

Lloyd Cluff provides a crisp summary of the December 26, 2004, tsunami and its aftermath, based largely on his own on-site survey and analysis. In the midst of the general devastation, he found numerous examples of sound engineering and construction that withstood both the earthquake and the tsunami waves.

Melvyn Green surveys types of owner-built structures in seismic areas. As he points out, improving building performance of existing owner-built buildings constructed with site-found materials would greatly reduce earthquake fatalities and damage. He suggests that improvements will require that nations work cooperatively to provide information to home owners and builders.

Because disasters are the results of social decisions, engineering strategies must be integrated with social-science and natural-science strategies. In addition, political leaders, NGOs, civic leaders, and many others must be involved in disaster preparedness and response. The paper by Tom O'Rourke, which is based on a presentation given at a colloquium on infrastructure and disaster-resilient communities, explains how resiliency fits into the continuum of responses and its implications for public policy.

As Hurricane Katrina demonstrated, engineering for the threat of natural disasters is not a matter for the public sector alone (whether at the local, state, or federal level). The private sector also plays a pivotal role. Private enterprise is a victim, an emergency responder, a mitigation planner, and a vector for propagating the effects of a disaster far beyond the area directly impacted. The private sector also operates much of the nation's critical infrastructure—communications, electrical and gas utilities, certain elements of water and transportation systems, and soft infrastructure, such as health care and financial facilities. In the final paper, Yossi Sheffi defines the characteristics of disaster-resilient enterprises. He argues that a comprehensive strategy for disaster preparedness must bring to bear the assets and issues of the private sector.

Finally, because disasters are social constructs that mutate in response to social change—population

increases and urbanization, the globalization of business, and advances in science and technology—engineers are faced with a moving target. Consider hurricanes. A century ago, they exacted a huge toll in lives because they were difficult to detect prior to landfall. Advances in monitoring and forecasting, beginning with ship-borne radio, changed that. A century ago, disasters were measured in fatalities and damaged and destroyed structures. However, urbanization, made possible by the development of critical infrastructure—communications, electrical power, gas, sewage, transportation, and water—has transformed the challenge. Hurricane disasters today are counted not only in fatalities and loss of physical property, but also in economic disruption. Hurricane Katrina, for example, triggered a spike in local—and national—gasoline prices. If the port of New Orleans had been compromised, countries worldwide would have experienced disruptions in shipments of U.S. grain.

Other examples are the New Madrid earthquakes of 1812 and the threat from space weather. The New Madrid earthquakes of 1812, the strongest this nation has ever experienced, discommoded a relative handful of fur traders and villages of indigenous peoples. Today, much of the natural gas infrastructure that supports the Northeast passes through that region. Space weather represents another entirely new vulnerability that did not exist prior to the invention of the telegraph and our dependence on electrical energy and regional power grids, long pipelines, and spaced-based technologies, such as weather monitoring, telecommunications, GPS, and transpolar flights.

The engineering community holds the keys to the future—which lies somewhere on a spectrum between a world in which natural hazards are a diminishing threat and a darker world in which natural extremes and disasters will seal the human fate.

Geotechnical conditions and design flaws both contributed to the failure of the levees in New Orleans.

Lessons from Hurricane Katrina

John T. Christian is a consulting engineer from Waban, Massachusetts, and an NAE member. This paper is based on a presentation by the author at the NAE Annual Meeting in October 2006.

John T. Christian

The social impacts of Hurricane Katrina have been covered extensively in the media. As of this writing (December 2006), at least four hardcover books on the subject have been published in addition to numerous newspaper articles and television programs. The effects of the storm on human life, emergency response, preparedness, and the future of New Orleans and the neighboring regions have properly been the principal focus of much of this coverage, but some attention has also been paid to the engineering aspects of the disaster—what happened, why it happened the way it did, whether the design and construction of the hurricane protection system were adequate, and what should be done in the future.

The volume of material just on the engineering aspects of the disaster is overwhelming. At least five boards of experts are reviewing the engineering problems, and the "draft final" report of one of them, the Interagency Performance Evaluation Task Force (IPET), runs to more than 6,000 pages. This paper provides a general overview of the results of these studies to date and then describes in more detail some issues of geotechnical engineering and the failure of the levees.[1]

[1] For more information on IPET, see *https://ipet.wes.army.mil/* and *http://www.usace.army.mil/*; *http://www.asce.org*. Information about the University of California, Berkeley, PEER Institute is available online at: *http://peer.berkeley.edu/PEERCenter/about.html*; the Louisiana State University Department of Civil Engineering is available online at: *http://www.cee.lsu.edu/eng/ceeweb.nsf/index*. For information on the joint NAE/NRC New Orleans Regional Hurricane Protection Projects, see *http://www8.nationalacademies.org/cp/projectview.aspx?key=335*. The New Orleans *Times-Picayune* is available online at *http://www.timespicayune.com*.

Boards of Experts

IPET (Interagency Performance Evaluation Task Force) was originally organized by the U.S. Army Corps of Engineers (USACE) and was then expanded to include participation by other government agencies and independent consultants. Prof. L.E. Link of the University of Maryland, formerly head of the USACE Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, chairs IPET. Shortly after the hurricane, the American Society of Civil Engineers (ASCE) also established a working group to review engineering issues associated with the hurricane. This group has developed a close working relationship with IPET and reviews IPET's work. Dr. David E. Daniel, president of the University of Texas at Dallas and a member of the National Academy of Engineering (NAE), chairs this committee.

In response to a request from the Assistant Secretary of the Army for Civil Works, NAE and the National Research Council (NRC) appointed an Engineering Review Committee (ERC) to review IPET's reports. Dr. G. Wayne Clough, president of the Georgia Institute of Technology and a member of NAE, chairs this committee. The author is one of the 16 committee members.

The National Science Foundation (NSF) funded a study by the PEER Institute at the University of California, Berkeley, on the behavior of the levee systems. Researchers from Berkeley and many other institutions participated in studies led by Berkeley professors Raymond B. Seed and Robert Bea (NAE). In addition, the geological engineering staff of the Department of Civil Engineering at Louisiana State University conducted its own evaluation of the design and performance of the levee systems. Professor Ivor van Heeren led the study.

What Happened

The Setting of New Orleans

We begin with a brief look at the geologic circumstances of the New Orleans area. The Mississippi River flows generally from north to south, but it takes a sharp turn to the east in northern Louisiana, passes through Baton Rouge and New Orleans, and disgorges into the Gulf of Mexico at a considerable distance east of the general north-south trend of the river. Over the last several thousand years, the delta has moved from place to place. It has been in its present location only for about the last 1,000 years. Left to its own devices, the river would revert to a more direct north-south pattern of flow, following the Atchafalaya River and discharging near the current location of Morgan City.

Because of the economic importance of Baton Rouge, Morgan City, and New Orleans, a system of levees has been constructed over the years to keep the river in its present bed, as well as to control its frequent flooding. To complicate matters further, flooding can result, not only from large spring flows in the Mississippi River, but also from storms that blow in from the Gulf of Mexico. Thus the designers and operators of a flood-control system for New Orleans are presented with complicated design conditions.

At New Orleans, the river flows essentially west to east (Figure 1). The city itself lies between the river to the south and Lake Pontchartrain to the north. The oldest parts of the city, including the French Quarter,

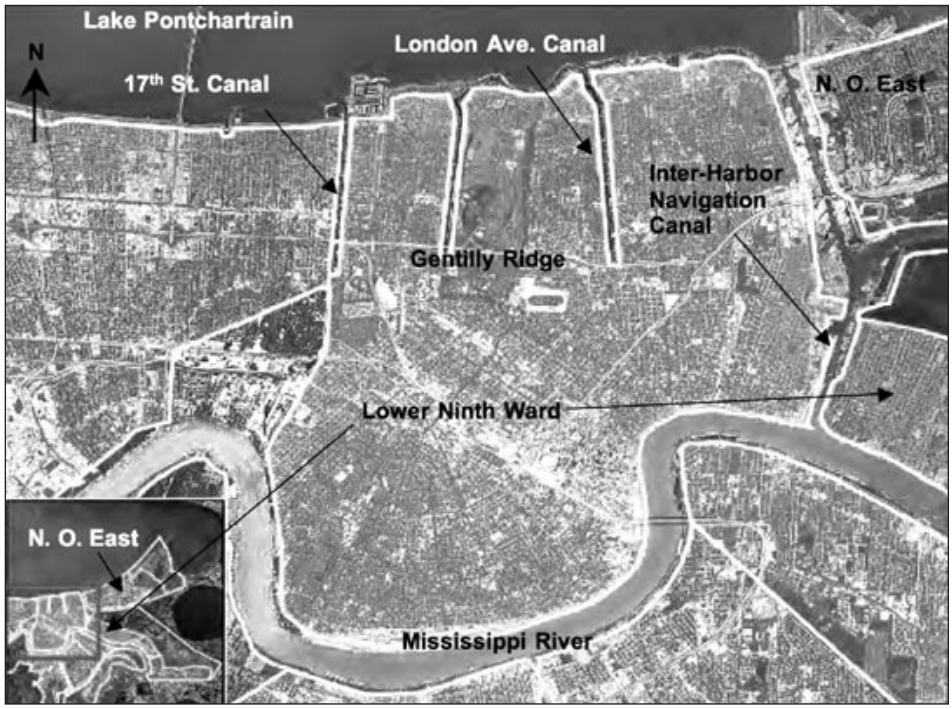

FIGURE 1 Map of New Orleans showing features important for understanding the effects of Hurricane Katrina. Adapted from IPET, 2006.

Garden District, Audubon Park, both Tulane and Loyola Universities, and the older residential sections, lie just north of the river along the high ground that forms the natural embankment of the river. About midway between the river and the lake is a gentle rise, called the Gentilly Ridge, that interrupts the general trend of falling elevation as one moves toward the low-lying lake. The region bounded by the ridge and the high ground near the river is thus a bowl, in which rainwater collects during heavy storms.

Early in the twentieth century, pumping stations were built along the ridge to remove floodwater from the basin. As the city expanded north beyond the ridge, the newly inhabited region north of the ridge was exposed to flooding from the lake. Instead of building additional pumping capacity at the lakeshore, the city connected the existing pumping stations to the lake via drainage canals. The city also expanded to the east, particularly into the areas known as New Orleans East and the Lower Ninth Ward. Almost all of these areas lie below sea level and must be protected by a system of levees.

Southern Louisiana has been built up out of sediments transported from the interior of the continent down the Mississippi River. Tens of thousands of feet of these soft sediments overlie crystalline bedrock. There is a general pattern of subsidence, complicated by additional settlement whenever a load, such as a levee, is placed on the sediments. Thus the city itself and individual structures settle by different amounts, so the tops of levees may actually be lower than the water levels they are supposed to defend against. Furthermore, because of the general subsidence, it is difficult to establish reliable benchmarks against which to measure the locations of levees.

Katrina's Track

Hurricane Katrina formed in the Atlantic Ocean in August 2005, moved west across southern Florida and into the Gulf of Mexico, then turned north. On August 29, the storm struck the mainland just east of New Orleans, very close to the border between Louisiana and Mississippi. When the center of the storm was in the Gulf south of New Orleans, its intensity reached Category 5 on the Saffir-Simpson scale. By the time the storm reached the mainland, its intensity had dropped to Category 3, so it is not strictly correct to say that New Orleans was struck by a Category 5 hurricane.

The Saffir-Simpson scale is based primarily on one-minute average wind velocity. It does not take into account rainfall, the storm's speed and direction, how long the storm remains over an area, the location of the center of the storm relative to the facilities of interest, or the geometry of the region affected by the storm. Although the scale is useful as a shorthand categorization of the severity of a storm, it does not provide a complete description and is certainly not adequate by itself for engineering design.

The tops of levees may be lower than the water levels they are supposed to defend against.

The Flooding

Three phenomena contributed to the flooding in New Orleans. First, the hurricane brought a large amount of rain. Precisely how much of the flooding was due simply to rainfall is still the subject of controversy, but it appears that something like one-third to one-half of the water that wound up in some of the bowls in New Orleans arrived directly from the heavens. Second, some of the levees were overtopped. That is, the level of water in the Gulf, Lake Pontchartrain, and other waterways around the city simply rose higher than the height of the levees, and the excess flowed over them. In many cases the overflow eroded the levee materials, destroying those sections of levee in the process. Third, some sections of levees or canals failed before the water level reached an overtopping level, and the horizontal component of the flow through the breaches added to the damage caused by the flooding. Spectacular examples include the failures of the 17th Street Canal, the London Avenue Canal, and the Inter-Harbor Navigation Canal. These phenomena combined to create flooding of 8 to 15 feet in the Lakeview section just south of Lake Pontchartrain, 10 to 13 feet in New Orleans East, and 12 to 15 feet in the Lower Ninth Ward.

Some levees were overtopped either because they were built to withstand a smaller storm than the one that actually occurred, they had settled below their design elevations, the consequences of the design storm had not been adequately estimated, or a combination of these effects. The levees that failed even before they were overtopped could not withstand even the water

levels for which they were designed. All of this suggests major deficiencies in the procedures for the design and construction of the levee system around New Orleans.

Emergency Reaction

It has become commonplace to say that emergency response and reconstruction efforts have been dysfunctional at all levels of government—city, state, and federal. Douglas Brinkley, in his book *The Great Deluge* (2006), observes that some agencies performed well. For example, the local Society for the Prevention of Cruelty to Animals had a policy that, upon learning of the approach of a Category 3 or greater storm, it would remove the strays under its protection to safety in other cities. The SPCA did precisely that and weathered the storm with no loss of the animals under its care.

Organizations empowered to protect humans performed poorly, but not for want of warning.

Unfortunately, the organizations empowered to protect human beings did not do as well, but not for want of warning. There is a large pre-Katrina literature on the exposure of New Orleans to flooding both from hurricanes and from the Mississippi River. Indeed, Brinkley points out that, immediately after its foundation in 1718, the city was struck by a hurricane, and the original settlers came close to abandoning the site. From June 23 to 27, 2002, the New Orleans *Times-Picayune* ran a series of articles entitled "Washing Away" that described the damage that could be expected if a major hurricane struck the city. In July 2004, barely more than a year before Katrina, the Federal Emergency Management Administration (FEMA) conducted a multi-agency exercise in emergency planning for the effects of a hypothetical Hurricane Pam. The literature on hazards to New Orleans is written in clear, nontechnical, forceful prose, and no thoughtful person should have been surprised by the severity of the storm's effects or the need for emergency planning.

Although the Hurricane Pam exercise led to the development of some emergency plans, they seem to have been abandoned or modified at the last minute as Katrina approached. The scenes of destroyed houses, drowned people, evacuees huddled in the Superdome amidst crime and filth, and so on are too familiar to require elaboration here. These conditions led to loud and bitter recriminations among government officials and private relief agencies at all levels. As this article is being written, the news still tells of thousands of unused FEMA trailers, uncertainties about reconstruction in New Orleans, questions about the way contracts for reconstruction were let, and continuing chaos in New Orleans' attempts to recover from the disaster.

So far, other than numerous reports in the press, no independent public examination has been done of what worked and what went wrong in the recovery and reconstruction effort. However, the engineering aspects of design, construction, and operation of the levee system have been reviewed.

Taskforce Guardian

As an interim measure, USACE set up Taskforce Guardian, whose mission was to restore the hurricane protection system to a satisfactory condition in anticipation of the 2006 hurricane season. The goal was to repair and upgrade the system as much as possible in the time available.

Some additional pumping stations and gates were built at the lakeside entrances to the drainage canals, and erodable materials in the levees were replaced. USACE officers stated explicitly that the system would not stand up to a Category 5 hurricane but should resist the more modest events that could be expected during the hurricane season. The construction of an ultimate robust system would have to wait for the completion of the IPET studies and the development of appropriate design criteria. The task force completed its work very shortly after the due date of June 1, 2006. In the actual event, no hurricanes struck the mainland in 2006.

Engineering Review of the Disaster

Although the five engineering review bodies operated independently, all of them reacted to IPET's work, the largest and best funded of the study groups. Volumes 2 through 7 of the IPET "draft final" report divide the results into six broad sections: Geodetic Vertical and Water Level Datums; The Hurricane Protection System; The Storm; The Performance of the Levees and Floodwalls; The Performance of Interior Drainage and Pumping; The Consequences; and Engineering and

Operational Risk and Reliability Analyses. The report is more than 6,000 pages long so far, and the last section on risk and reliability has not yet appeared. The NAE/NRC team and the ASCE team both organized their comments to conform to the IPET pattern.

In reviewing a study of this sort, it is important to keep in mind that critiques may address the quality of the design and construction for facilities in place at the time of the hurricane or the adequacy of the post-hurricane investigations described in the report. For example, one might find that the wind and water levels used for the design calculations were not adequate but that the hind-casting calculations of the hurricane's effects described in the report are excellent. The NAE/NRC team and the ASCE team had similar reactions, with some minor differences of detail.

The detailed study of the geodetic levels revealed considerable room for confusion and error. Two different benchmark levels were used in creating the levee system. In some cases, the water levels were expressed against one benchmark and the height of the levees against another. Furthermore, there seemed to be no consistent effort to monitor subsidence of the levee system or its components. The focus was on building the levees to the "authorized" elevations without considering whether the corresponding water elevations were measured from the same base or whether subsequent settlement and subsidence might make the authorized levels irrelevant.

All of the review teams found that the hurricane protection system was a system in name only. Planning and system-wide design were confused by political and short-term economic considerations over a period of several decades. In such an environment, it is almost impossible to plan rationally, and a number of basic questions were not addressed. For example, detailed design was based on the parameters of a "standard project hurricane" (SPH), which changed over the years as the city experienced more hurricanes. Although the annual risk represented by the SPH was never clear, it was invoked in congressional authorizing legislation. Similarly, little effort was made to establish target factors or margins of safety that corresponded to actual risks.

The IPET study included an extensive computerized calculation to recover the history of Hurricane Katrina, which yielded detailed descriptions of the wind velocities and water elevations throughout the storm. These calculations confirmed that the particular track taken by the storm caused it to pass near the eastern system of levees and to become positioned near the eastern entrance to Lake Pontchartrain, which generated surges of water that overtopped the eastern levees and drove water up the drainage canals. This part of IPET's work has shown that the behavior of hurricanes can be hind-cast or predicted with modern finite-element and finite-difference methods and that they should be used in future to develop design loadings.

Two different benchmarks were used in creating the levee system.

Evaluating the performance of the protection systems involved detailed studies of the mechanics of various failures. IPET dealt primarily with the failures of the 17th Street Canal and the London Avenue Canal, but some attention was focused on other failures as well. These back-analyses of levee failures were difficult because water rushing through the breaches eroded much of the evidence, making it nearly impossible to determine the precise conditions at the time of failure. The IPET group used conventional limit-equilibrium analyses with circular failure surfaces, finite-element simulations, and centrifuge simulations to study the levee failures (Figures 2 and 3). Other groups relied primarily on limit-equilibrium analyses.

The soil profile differs from location to location, but the situation at the 17th Street Canal failure is typical. The levees, which run north-south along the sides of the canal, are composed of clayey soils resting on a layer of peat (called marsh material in the IPET report), which in turn lies over lacustrine clay and then a sandy beach deposit. To attain the desired level of protection, "I-walls" (steel-sheet piling or reinforced-concrete panels) extending several feet above the levee embankments were embedded in the levees.

An essential ingredient in stability analysis is the description of soil strength. The general consensus is that the design of the levees was not based on conservative estimates of soil strength. The original geotechnical reports showed very wide scatter in the measured values of shear strength. This scatter, rather than indicating variability of the soil, is more likely to reflect errors in

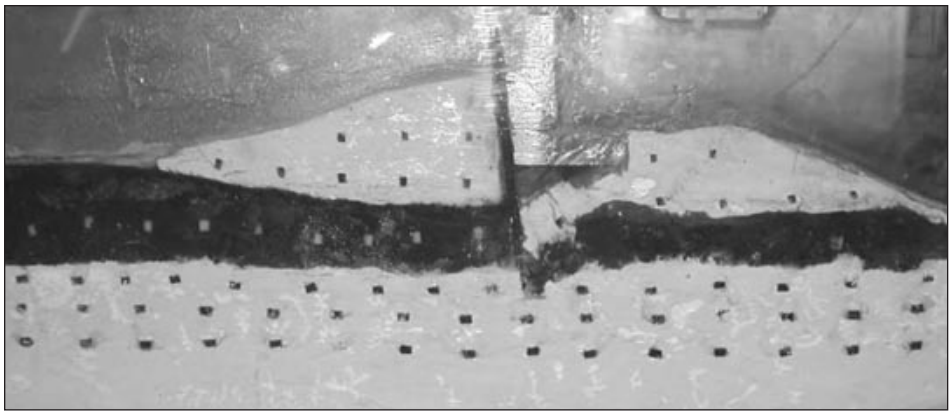

FIGURE 2 Failure of model in a centrifuge test run at Rensselaer Polytechnic Institute. The original figure has been reversed to show the failure occurring from left to right to conform to Figure 3. Note the relative displacement of the top layer of markers in the lower clay layer to the left of the sheeting. SOURCE: IPET Draft Final Report.

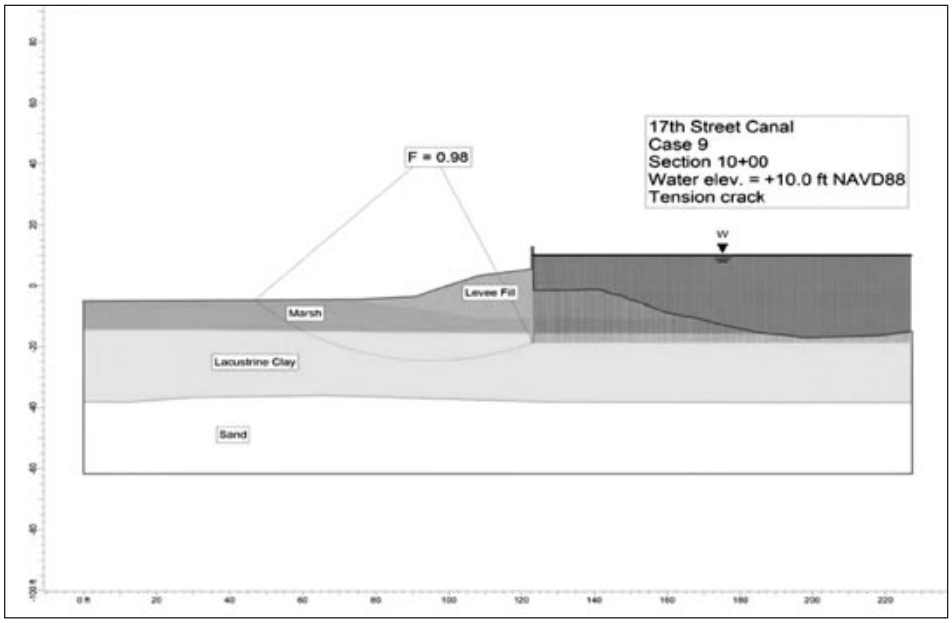

FIGURE 3 Results for critical circular failure surface from an IPET limit-equilibrium stability analysis showing a gap between the wall and the upstream embankment. SOURCE: IPET Draft Final Report.

drilling, sampling, and testing procedures. More modern investigations using piezocones yielded much less scatter. The original designers not only failed to use conservative soil strengths for the analyses, but also failed to account adequately for the fact that the soil under the toe of an embankment should be weaker than the soil under the crest, where the weight of the embankment compresses it to a greater density.

All of the investigations showed that the levees were either unstable or marginally stable. This is not surprising because all of the analysts knew that the levees had in fact failed. However, different groups arrived at different mechanisms of failure. Centrifuge tests, carried out at Rensselaer Polytechnic Institute and the USACE Engineer Research and Development Center, demonstrated failure along a nearly horizontal plane near the top of the lacustrine clay. In these tests, the I-wall moved downstream as a result of the pressure of rising water in the canal and opened a gap between the wall and the upstream portion of the levee embankment. Water flowing into that gap then applied the full hydrostatic head to the wall. The IPET limit-equilibrium analyses could not recapture failure conditions until they too assumed the existence of the gap and upstream water levels higher than those observed in the field during the storm. The Berkeley PEER group concluded that the failure had not occurred through the clay but had followed a weak seam in the peat. Other groups postulated variations on these failure mechanisms.

In summary, examinations of the levee failures have revealed several plausible failure mechanisms, including a weaker than anticipated clay layer, a soft zone in the marsh material, the effects of a "crack" between the wall and the upstream part of the embankment, differential settlement of the levees and neighboring structures, seepage forces, and even the consequences of toppled trees pulling up their roots.

All of these explanations are at least plausible, but it is hard to identify the actual culprit. Different effects may be dominant at different sections of a levee, and more than one effect may have contributed to several failures. Some sections may have held, not because they

were safe but because another section of the levee failed first and relieved the load. In any case, it is clear that the design of many of the levees was, at best, marginal and that the procedures for designing and building levee systems need to be improved. Design criteria, such as safety factors, must be based rationally on the consequences and probabilities of failure and not simply on past practice.

Conclusions for the Future

All five review panels agree in one way or another that the engineering of the levee system was not adequate. The procedures for designing and constructing hurricane protection systems will have to be improved, and the designing organizations must upgrade their engineering capabilities. The levees must be seen not as a system to protect real estate but as a set of dams to protect people.

There must be independent peer reviews of future designs and construction. The Board of Inquiry into the 1928 failure of the Saint Francis Dam concluded that no dam whose failure could cause such a large loss of life should be based on the judgment of one man and that independent review boards should be required for all dams in California. Almost identical language can be found in the report of the federal review panel for the 1977 failure of Teton Dam. Hurricane Katrina demonstrates again that independent peer review of the design, construction, and operation of critical infrastructure systems should be required. Current indications are that USACE is adopting this philosophy.

Emergency response and reconstruction efforts after Katrina were poorly organized, even dysfunctional. Recovery efforts continue to be plagued by confusion, disorganization, and recriminations. Unfortunately, these aspects of Hurricane Katrina have received much less systematic attention than the engineering issues. There is no "Interagency Response and Recovery Evaluation Task Force" corresponding to IPET. Adequate responses to future disasters will require that the failures of emergency procedures and recovery efforts for Hurricane Katrina be subjected to the same kind of independent, public examination as the engineering performance.

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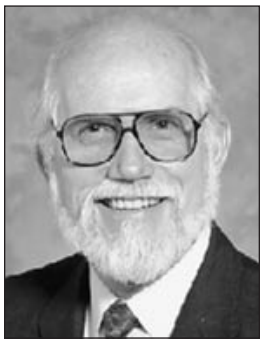
This eyewitness assessment of damage from the earthquake and tsunami yields lessons for engineers.

Effects of the 2004 Sumatra-Andaman Earthquake and Indian Ocean Tsunami in Aceh Province



Lloyd S. Cluff is director of geosciences and earthquake risk management, Pacific Gas and Electric Company, and an NAE member.

Lloyd S. Cluff

On December 26, 2004, at 07:58:50 local time, a powerful earthquake, moment magnitude (M_W) 9.2, occurred in the Indian Ocean. The Sumatra-Andaman earthquake was one of the three largest earthquakes ever recorded. The fault rupture propagated 1,300 to 1,600 kilometers northwest for about 10 minutes along the boundary between the Indo-Australian plate and the Eurasian plate, from northwestern Sumatra to the Nicobar Islands and to the Andaman Islands. The hypocenter, the point where the fault rupture originated, was 10 kilometers deep. The faulting spread updip and downdip from 18 to 25 meters on a low-angle thrust fault plane dipping about 10 degrees northeast. The Indo-Australian plate moved northeast relative to the Eurasian plate. Several excellent papers have been written on the tectonics of the earthquake (e.g., Lay et al., 2005), and the seismological, geologic, and geodetic aspects have been comprehensively described by Kanamori (2006) and Hudnut (2006).

The resulting tsunami affected 12 nations around the Indian Ocean, with Indonesia suffering the greatest damage. In Aceh, the northern province of Sumatra, the United Nations (UN) Field Office reported approximately 131,000 people confirmed dead and 37,000 missing. With more than 80,000 houses sustaining major damage or collapse, the UN estimated that more than 500,000 people were displaced from their homes in Sumatra alone. In addition to the massive damage to housing, utilities, roads, and bridges,

FIGURE 1 Aerial view of western Aceh Province near Calang showing the effects of tectonic subsidence.

the disaster significantly disrupted the social fabric and government of the affected communities.

Shaking Damage

The epicenter of the earthquake was about 250 kilometers off the west coast of Aceh Province. Strong to violent shaking in Aceh Province reportedly lasted five to six minutes. Banda Aceh was the only major city that experienced earthquake-shaking damage. One- to two-story, traditional, concrete-frame and wood-frame buildings survived well and were largely undamaged by the strong ground shaking. However, because the earthquake occurred a significant distance offshore, the resulting long-period ground motions caused serious damage to, or the collapse of, buildings more than three stories high.

Fault Deformation

A compounding problem was tectonic subsidence resulting in 20 to 100 centimeters of down-warping of the Earth's crust beneath the Aceh region. The subsidence extends for at least 280 kilometers along the entire northwestern Aceh coast (Figure 1). This submergence thwarted rescue efforts and has hindered the restoration of roads, bridges, and utility distribution systems.

Tsunami Damage

The fault rupture uplifted the ocean floor, releasing the most destructive series of tsunami waves in recorded history. The waves spread throughout the Indian Ocean, causing damage in the coastal communities of 12 countries. By far, the most damaging effects were sustained by Aceh Province, where three devastating waves struck the western shore within about 30 minutes. The tsunami waves ranged from 4 to 39 meters high and destroyed more than 250 coastal communities.

In the low-lying areas of western coastal Sumatra, including the city of Banda Aceh, the tsunami waves extended inland as far as 5 kilometers, affecting a large portion of the population of 300,000. The western part of the city has nearly flat topography traversed by rivers and drainage channels. In these areas, the maximum wave-flow height was 4 to 8 meters. In hilly areas south of Banda Aceh, the wave-flow height was significantly greater, due to the topography.

Residential neighborhoods and fishing villages in coastal areas were entirely devastated, and houses were swept inland or out to sea. The traditional construction that had resisted shaking damage could not resist the tsunami forces and most were obliterated. Figure 2 shows what was left of most houses—mostly the concrete floor slabs. The tsunami waves left extensive piles of timber and the remains of buildings.

Most well designed and well constructed buildings and industrial facilities that had withstood the earthquake

FIGURE 2 Aerial view of western Banda Aceh showing an area devastated by tsunami waves. Only concrete floor slabs of most houses remain.

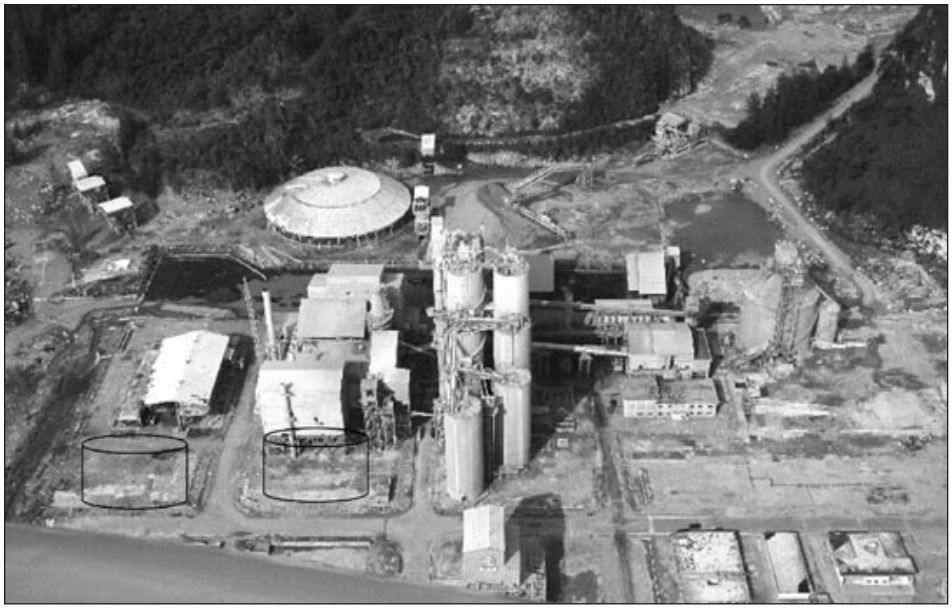


FIGURE 3 Aerial view of the La Farge Cement Plant. When the tsunami waves arrived, empty fuel tanks, indicated on the bottom left of the photo, became buoyant and destroyed small buildings to the right. The empty tanks also collided with the steel-reinforced cement silos but glanced off without damaging them.

shaking also withstood the tsunami waves and suffered only minor damage. For example, the La Farge Cement Plant (Figure 3), a well designed and well constructed steel-frame series of industrial structures about 20 kilometers southwest of Banda Aceh, did not experience structural damage from the strong shaking and was not damaged by the tsunami waves, which, as documented by stadia-rod, reached a wave-flow height of 38.9 meters nearby. Several one- and two-story administrative buildings and machine shops were smashed by waves carrying nearly empty large oil-storage tanks. The impact of the waves caused non-structural damage to some of the buildings. For example, metal siding was stripped from the steel-frame buildings up to the height of the waves (Figure 4).

Figure 5 shows a typical mosque south of Banda Aceh, which was impacted by 5-meter-high tsunami waves. Inspection revealed that the quality of construction and of the concrete in most mosques was excellent. Most have steel-reinforced concrete frames as load-resisting systems, along with domes and open arches that allowed tsunami waves to traverse the space without causing serious damage.

The low-lying topography of Banda Aceh and surrounding areas and the height of the water resulted in debris being swept in and out by the three successive destructive tsunami waves. This caused large, heavy projectiles, such as cars, trucks, and fishing boats, to be swept in and out, each time impacting previously undamaged facilities. Many small buildings were structurally damaged by tsunami waves carrying floating debris.

FIGURE 4 The La Farge Cement Plant was a well designed steel-framed structure anchored to rock. The metal siding was stripped from the buildings up to the wave-flow height of ~35 meters.

FIGURE 5 Intact mosque near Banda Aceh.

FIGURE 6 Miracle boat that saved the lives of 53 people in Banda Aceh.

A large number of fishing boats were docked at the coastal and river locations that traverse the city. Fishing boats were torn from their moorings and cast inland during the tsunami. One boat that was permanently docked on the second story of a house (Figure 6) saved 52 people, who were able to climb through the roof-hatch and take shelter there; inside, they found a stranded security person in the captain's quarters.

Electric Power

Most well designed and well constructed electric power plants in Aceh Province did not experience structural damage from the earthquake or tsunami. The electric generating facilities experienced light damage to the generating capacity and no damage to the transmission network. However, there was substantial damage to the distribution network in the affected area. Most above-ground distribution systems were seriously damaged or destroyed by the tsunami. Damage to the power supply was concentrated in western Aceh Province, along low-lying areas in Banda Aceh and toward the south along the west coast to just beyond Meulaboh. The main damage was to the power distribution networks (small substations and hollow-core distribution poles). About 170,000 customers were affected by loss of power in Banda Aceh and along the low-lying coastal plain to Meulaboh.

Indonesia's public electric supply is provided by PT PLN, the state-owned electric company. Banda Aceh's electric power comes from the Aceh regional electric grid and, in central Banda Aceh, the Luengbata diesel-generation plant (50-megawatt, 11 units), which reported damage only to some generation transformers. An 11-megawatt diesel-generating station, mounted on a barge offshore, was swept inland more than 3 kilometers from the harbor in Banda Aceh by tsunami wave action. Although the power plant was undamaged, it left a path of destruction of houses and commercial buildings as it charged inland. PT PLN plant operators informed us that neither the intense shaking nor the 3 kilometer transport of the barge-station was the reason the plant was not operating; the main problem was lack of demand. PT PLN reported that electric power was restored to most emergency-response customers in Banda Aceh within three days and to the remaining customers within about two weeks.

PT PLN reported that the electric system generally was not affected by earthquake shaking, except for the newly built headquarters building, which was more than three stories high and had to be abandoned. The tsunami did not affect the 150-kV substation or the inland diesel-generating power stations. A small (1 megawatt) diesel-powered plant was destroyed at Calang, directly on the coast about halfway between Banda Aceh and Meulaboh. The Meulaboh Lamno diesel plant did not experience significant damage. The 150-kV transmission line and associated substations transmitting power from power plants to the east functioned normally during and after the earthquake and tsunami. In fact, the electric power in western Aceh Province did not shut down. Some PT PLN emergency-response workers were electrocuted when they attempted to restore electricity to emergency facilities because they had assumed the tsunami had tripped the power supply.

Gas and Liquid Fuel Facilities

The state-owned Pertamina petroleum company suffered substantial damage to fuel depots, where storage facilities were damaged and some fuel was lost, mostly on the west coast of Aceh Province, particularly in Banda Aceh and south to Meulaboh. The deep-water port at Kreung Raya, the petroleum storage and distribution facility, lost half of its above-ground piping and 3 of 12 liquid fuel (diesel, high-octane gas, oil, and kerosene) storage tanks. None of the tanks was anchored to its foundations, and the three that were swept away by tsunami waves were only partially full. The nine full storage tanks were not affected. As with the electric system, most above-ground distribution systems were seriously damaged or destroyed by the tsunami.

Roads and Bridges

Roads and bridges were devastated by the force of the tsunami waves. Many bridges were swept off their supports, and connecting earth embankments were

significantly scoured, disabling the transportation network for hundreds of kilometers along the west coast of Aceh Province. Hundreds of bridges were picked up and swept inland by the tsunami waves, some more than a kilometer. The extensive damage to bridges severely constrained rescue and relief efforts, as the bridges had been vital links to population centers in the region. Many of the bridges on the coastal road to Meulaboh were destroyed and washed away, and sections of the road disappeared, which isolated many small communities. Survivors could be reached only by boat or helicopter. In addition, the destruction of the bridges resulted in the disruption of the electric distribution system at bridge crossings.

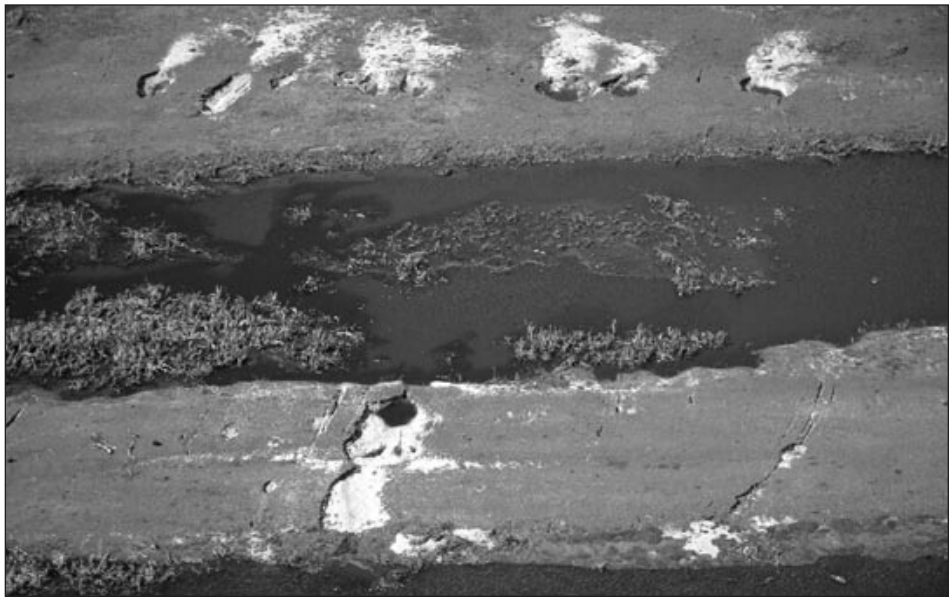


FIGURE 7 Aerial view of a coastal region north of Meulaboh showing coastal plain underlain by water-saturated loose deposits of beach sand that had experienced liquefaction. Sand blows were scoured by tsunami wave action.

Liquefaction

Although earlier reconnaisances reported no evidence of liquefaction, earthquakes of this magnitude and duration commonly cause liquefaction in coastal areas. During a reconnaissance by helicopter, we observed extensive liquefaction in near-shore beach deposits for at least 150 kilometers along the Aceh coast, from south of Meulaboh to north of Calang. Figure 7 shows massive earthquake-induced sand-blows, with craters scoured by tsunami wave action. These liquefaction effects may have been the deciding factor in the destruction of the PT PNL 1-megawatt power plant on the coast at Calang.

Conclusions

Although routinely constructed houses and buildings may have been able to survive the earthquake shaking, tsunami waves devastated almost all of them. Most well designed and well constructed utility and industrial facilities had sufficient capacity to withstand both the earthquake and the tsunami. Partially full storage tanks, bridges, and other light structures that were not anchored to their foundations were not able to resist tsunami forces. Tectonic subsidence and liquefaction were significant contributors to the devastation.

Acknowledgments

This paper is based on a team (Lloyd Cluff, George Plafker, and Stuart Nishenko) reconnaissance, sponsored by Pacific Gas and Electric Company, to Aceh Province, Indonesia, in May 2005, almost five months after the December 26, 2004, earthquake and tsunami. The purpose of the investigation was to assess the performance of gas and electric systems and related industrial infrastructure. Our reconnaissance focused on northern Aceh Province, where the earthquake and tsunami effects were most severe.

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More information on constructing simple, seismically safe buildings could go a long way toward reducing fatalities.

Engineering Research for Non-Engineered Buildings

Melvyn Green, a structural engineer, is president of Melvyn Green & Associates Inc., Torrance, California. This paper is based on a presentation by the author at the NAE Annual Meeting in October 2006.

Melvyn Green

Studies of recent earthquakes have confirmed that loss of life occurs principally in single-family dwellings of unreinforced masonry, usually constructed by owners or local masons with site-found materials, such as ashlar or rubble stone, earth (adobe), or manufactured masonry block or brick. The 2005 earthquake in Pakistan resulted in more than 75,000 deaths from building collapses, primarily in rural dwellings and schools constructed mostly of stone and some manufactured masonry, some with a concrete bond beam and columns at corners, most with concrete roofs. The recent earthquake in Iran had similar results, but the structures there were constructed of earth rather than stone.

After disasters, many nations and organizations provide short-term and long-term relief. Donor organizations, such as the World Bank, which often provide or pay for replacement housing, want new structures to be earthquake-resistant both to ensure the safety of the occupants, and possibly to protect their investments. Plans for replacement buildings often call for concrete-masonry unit walls and concrete or wooden roofs. Although this kind of construction may be feasible in urban areas and towns and villages near roads, it may not be feasible in many other places. In the earthquake zone of Pakistan, for example, many villages are accessible only by trail. Thus construction materials for earthquake-resistant buildings would have to be carried long distances by hand or, at best, by mule. As a result, villagers often

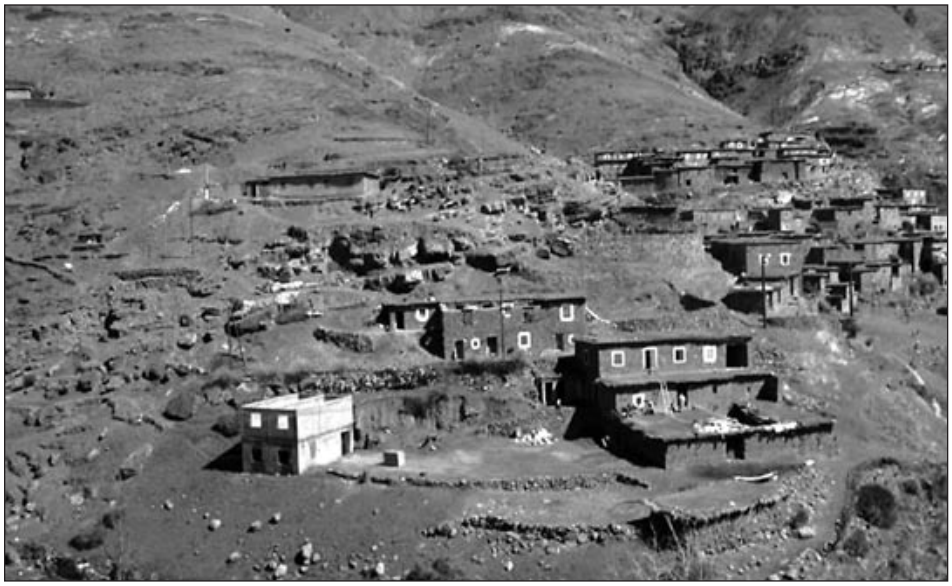

FIGURE 1 Earthen buildings in a Morrocan village.

reconstruct or replace destroyed or damaged buildings using the same methods and materials that were used in the original construction.

One of the problems for people in remote, earthquake-prone areas is a lack of information about how to improve construction. In fact, most engineering research has been focused on the seismic rehabilitation of large, multistory structures rather than low-rise masonry and earthen buildings, and very little information is available on how to construct a simple building with built-in seismic safety.

Earthquake Response in the United States

Earthquakes in the United States have been followed by federally funded research to provide guidance to engineers on seismic strengthening. The loss of life in brick buildings in past earthquakes, particularly the 1971 Sylmar (Los Angeles area) earthquake, led to a research project funded by the National Science Foundation (NSF) carried out by a team with members from Agbabian Associates, S.B. Barnes and Associates, and Kariotis and Associates (ABK). Focused on unreinforced masonry buildings with wood-framed roofs and floors, the results of the project were reviewed by the professional community and later adopted into building codes. This earthquake-resistant construction, initially permitted by the city of Los Angeles as a "special procedure," has since gained acceptance and is now included in the Uniform Code for Building Conservation and the International Existing Building Code. The "special procedure" has been the basis for strengthening several thousand brick buildings. Although these provisions have not brought buildings up to current building code standards, they have reduced the chances of death and injury in earthquakes.

The 1994 Northridge (Los Angeles area) earthquake caused significant damage to steel-moment-frame building connections. In the aftermath, the Federal Emergency Management Agency (FEMA) funded research by a joint team of the Applied Technology Council (ATC), California Universities for Research in Earthquake Engineering (CUREE), and the Structural Engineers

FIGURE 2 Remains of a rammed-earth building.

Association of California (SEAOC) to test and evaluate steel-moment connections (see *http://www.sacsteel.org/*). This research led to a different detailing of steel joints for new buildings—several so-called FEMA connections and proprietary designs. Numerous other post-earthquake studies of concrete buildings have focused on beam-column joints and lightly reinforced buildings. In other parts of the world, however, much less has been done, especially for single-family dwellings and low-rise buildings.

Earthen Buildings

Earthen buildings constructed of a mixture of sand and silt with clay as the binder are found on all continents and in all countries (Figure 1). The most common types of earthen construction are adobe and rammed earth.

Adobe bricks are made in a mold and are usually 16 to 20 inches long and 8 inches or more wide, a size that can be lifted by one person. Adobe buildings are constructed in a running-bond pattern with a mortar of adobe mud between blocks.

In the rammed-earth construction method (Figure 2), earth is packed into forms in a manner similar to the placement of concrete. The side of a formed unit may be as much as 4 feet high by about 6 feet long, depending on the thickness of the wall. Joints between units are packed with mud.

Historically, a bond beam, usually of wood, was used in earthen buildings. In the seismic zones of California, a concrete bond beam, or collar, is constructed at the top of walls, usually at the roof line; in some buildings, a parapet may be constructed above the bond beam. In recent years, engineers in California have attached the bond beam to the wall with vertical connector rods. However, in many places around the world, the bond beam is not connected to the wall at all.

Entire villages around the world are constructed using these methods. Some research has been done on the seismic behavior of adobe construction in several countries, including Peru and the United States. The Getty Conservation Institute, through its Getty Seismic Adobe Program (GSAP), has supported testing of adobe construction and has published the results in several reports (Tolles et al., 2000).[1]

[1] More information about the Getty Seismic Adobe Program is available online at: *http://www.getty.edu/conservation/publications/newsletters/11_1/news1_1.html*.

Stone Buildings

In mountainous areas, stone has been the traditional construction material for walls. Stone walls are erected as typical masonry lay-up with bond blocks between wythes (Figure 3). In some cases buildings are constructed with single-wythe or unbonded, multi-wythe construction. The roof is constructed of wood trusses with a metal covering. Some later buildings were constructed with concrete bond beams and concrete corner columns (Figure 4). Many also had concrete roofs. A significant number of stone buildings collapsed in the Pakistan earthquake. Inspections after the earthquake revealed that the majority of collapsed buildings were the unbonded, single-wythe construction. These buildings did not have direct connections between bond beams and the stone walls, which might have reduced the number of collapses.

FIGURE 3 Stone structures in a Morrocan village.

FIGURE 4 Collapsed building showing remains of a concrete bond beam.

Brick Masonry Buildings

Brick construction, which is widely used in many countries, also has been the cause of many deaths and injuries in earthquakes. Research in the United States

FIGURE 5 A school in Delhi, India, built of brick masonry scheduled for seismic rehabilitation.

has led to many improvements; India has also developed strengthening procedures.

In the United States, strengthening is based on the unreinforced wall acting as a vertical beam between the floor and the roof, or between floors in multistory structures. Connections to the roof and floors keep the walls in place.

In India, instead of a roof or floor diaphragm to brace the walls, the walls are allowed to span horizontally to perpendicular walls (Figure 5). The spacing between walls is limited and is within the traditional building wall-spacing, reflecting cultural preferences. In addition, seismic bands made of wire mesh plastered with a thin layer of concrete are placed at the roof, sill, and window lintel lines, and vertically at corners (Figure 6). This type of construction appears similar to the bond-beam approach, with additional ties at points where failures may occur. Interestingly, the placement of the seismic bands appears to be in line with research results on adobe buildings. It is not clear if this seismic-band type of construction is effective in all seismic zones, however.

Concrete Buildings with Masonry Infill

A common construction type used worldwide, especially for low-rise structures, is a concrete "frame" with unreinforced masonry infill. The "virtual diagonal strut" concept, in which the wall is regarded as a diagonal brace, is one way of evaluating such structures. Another is to consider the building a shear-wall structure. Out-of-plane loads require positive connections, usually epoxy-adhered bolts and metal connectors, between the wall and the bracing diaphragms.

Research Needs

It may not be possible to provide the levels of safety (life safety in the 475-year event and collapse prevention in the 2,500 year event) as envisioned in U.S. building codes for owner-built structures in other parts of the world. Nevertheless, all of the construction types outlined in this paper can be improved.

A number of studies and projects have been carried out over the years around the world, and many countries have assembled, or are assembling, building code provisions for different types of construction. However, these efforts have not been coordinated so that engineers and code authorities can make effective use of them. The Earthquake Engineering Research Institute online *World Housing Encyclopedia*[2] may be a potential resource and repository for such information.

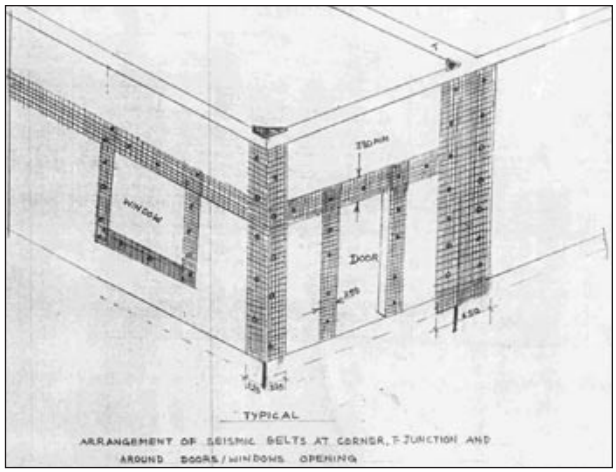

FIGURE 6 Drawing showing seismic bands for an existing building.

It has been suggested that a deterministic approach be taken in analyzing simple, low-rise buildings. This would involve reviewing how these buildings fail and determining the sequence of failure. For example, we are aware that connections between elements are critical, and research might be directed toward improving connections between bond beams and walls. Another study might determine if a corrugated metal roof could be mobilized to act as a diaphragm with simple connections.

Another study might focus on improving single-wythe masonry with connections or stiffening elements to make structures safer. We also need guidelines for

[2] Available online at: *http://www.world-housing.net/*.

improving connections and the performance of low-rise, concrete frame buildings with masonry infill.

Summary

Improving existing owner-built buildings constructed with site-found materials would improve building performance and reduce the number of deaths and amount of damage in earthquakes. Cooperative efforts among nations could provide information to building owners and builders. Activities could be conducted by regional groups working with world bodies such as the United Nations or with individual countries.

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Resilient physical and social systems must be robust, redundant, resourceful, and capable of rapid response.

Critical Infrastructure, Interdependencies, and Resilience

T.D. O'Rourke is the Thomas R. Briggs Professor of Engineering at Cornell University and an NAE member.

T.D. O'Rourke

The concept of critical infrastructure is evolving. In the 1980s, concerns about aging public works led the National Council on Public Works Improvement (1988) to focus on infrastructure in the public sector, such as highways, roads, bridges, airports, public transit, water supply facilities, wastewater treatment facilities, and solid-waste and hazardous-waste services. In the 1990s, as a result of increased international terrorism, infrastructure was redefined in terms of national security. After 9/11, the number of "critical" infrastructure sectors and key assets listed in the National Infrastructure Protection Plan was expanded to 17 (DHS, 2006). The list includes agriculture and food systems, the defense-industrial base, energy systems, public health and health care facilities, national monuments and icons, banking and finance systems, drinking water systems, chemical facilities, commercial facilities, dams, emergency services, nuclear power systems, information technology systems, telecommunications systems, postal and shipping services, transportation systems, and government facilities.

Adjusting the definition to reflect current concerns has provided for flexibility and adaptability but has also led to some ambiguities about which assets are critical and which criteria should be used to define them. In addition, the proliferation of critical-infrastructure sectors has added complexity to an already complex field. To develop basic principles that govern performance and clarify interactions, it is helpful to consolidate our thinking into

unifying concepts and a smaller number of sectors based on common traits.

The concept of a "lifeline system" was developed to evaluate the performance of large, geographically distributed networks during earthquakes, hurricanes, and other hazardous natural events. Lifelines are grouped into six principal systems: electric power, gas and liquid fuels, telecommunications, transportation, waste disposal, and water supply. Taken individually, or in the aggregate, all of these systems are intimately linked with the economic well-being, security, and social fabric of the communities they serve. Thinking about critical infrastructure through the subset of lifelines helps clarify features that are common to essential support systems and provides insights into the engineering challenges to improving the performance of large networks.

Interdependencies

Lifeline systems are interdependent, primarily by virtue of physical proximity and operational interaction. Consider Figure 1, for example, a photograph of the corner of Wall Street and Williams Street in New York City in 1917. The congestion shown in this photograph has not improved in the last 90 years, and similar locations can be found in a multitude of cities worldwide. Critical systems in crowded urban and suburban areas like these are subject to increased risk from proximity. Damage to one infrastructural component, such as a cast-iron water main, can rapidly cascade into damage to surrounding components, such as electric and telecommunications cables and gas mains, with system-wide consequences.

To complicate matters, much of this critical infrastructure is underground, which obscures the location and condition of components. The proximity of aging, weakened pipelines to other important facilities, such as high-pressure gas mains and electric power substations, is frequently not recognized, increasing the potential for unanticipated accidents for which no preparations have been made.

Lifeline systems all influence each other. Electric power networks, for example, provide energy for pumping stations, storage facilities, and equipment control for transmission and distribution systems for oil and natural gas. Oil provides fuel and lubricants for generators, and natural gas provides energy for generating stations, compressors, and storage, all of which are necessary for the operation of electric power networks. This reciprocity can be found among all lifeline systems.

The use of electric power at pipeline pumping stations is especially important. After Hurricane Katrina, the supply of crude oil and refined petroleum products was interrupted because of a loss of electric power at the pumping stations for three major transmission pipelines: the Colonial, Plantation, and Capline Pipelines. As a result, major lines of refined products were not available for delivery to southern and eastern states, and gasoline and diesel production in the Midwest was seriously affected by lack of supply. About 1.4 million barrels per day of the crude oil supply were lost, accounting for 90 percent of the production in the Gulf of Mexico. Nearly 160 million liters per day of gasoline production was lost, accounting for 10 percent of the U.S. supply. The three major pipelines were not fully restored until September 14, 2005, more than 17 days after Katrina made landfall in southern Louisiana.

FIGURE 1 Underground infrastructure at Wall Street and Williams Street in New York City, 1917. Source: Consolidated Edison Company of New York, Inc.

Similar difficulties have been experienced at water-supply pumping stations. After the 1994 Northridge earthquake, electric power was lost for nearly 24 hours in the Van Norman complex, which receives and treats about 75 percent of the potable water for the city of Los Angeles. As a result, the largest water pumping station in the city system could not be operated. A smaller station where pumps were activated by combustion engines made up for some of the loss. Note, however, that the amount of fuel that can be stored on site at pumping stations, even facilities equipped with combustion engines, is often restricted by environmental regulations. Thus, if fuel runs out, refueling depends on the transportation system, which is also likely to be damaged and difficult to negotiate after a disaster.

The World Trade Center Disaster

The World Trade Center (WTC) disaster has been studied in detail with respect to structural failure, building performance, and the impact of fire on building integrity. WTC also has lessons for lifeline performance and interdependencies. When the twin towers collapsed, water mains servicing the WTC complex were ruptured primarily by falling debris and impact. Records of water flow to the WTC area and nearby neighborhoods show that immediately after the buildings collapsed, water flow suddenly increased by 210 million liters per day, then rose gradually another 30 million liters per day (O'Rourke et al., 2003). The initial jump was caused by water pouring through broken water mains beneath and around the WTC complex. The additional flow represents, approximately, the amount of water drawn from fire hydrants to fight fires in adjacent buildings. Water pressures at hydrants around the WTC complex declined throughout the afternoon. Measurements at 6:00 p.m. showed pressure two to three blocks from the site at approximately one-third of normal. Of course, firefighting was impaired by the falling pressure.

The primary source of water at the WTC complex was fireboats on the Hudson River. Figure 2 is an aerial view of the WTC site, showing the deployment of four fireboats (*Firefighter, McKean, Kane, and Smoke II*). The tie-up locations and hose paths are shown for each boat. Although the combined pumping capacity of the fireboats was 180,000 liters per minute, only a small fraction of that, approximately 28,000 liters per minute, was conveyed to the WTC complex, partly because the water was relayed through relatively small hoses (90-mm and 125-mm-nominal-diameter) (O'Rourke et al., 2003). Nevertheless, water from the fireboats was about 150 percent of the water available from hydrants and was critical to containing and extinguishing fires on the site.

Water from the ruptured underground pipelines flowed into the underground sections of the WTC complex and flooded the Port Authority and Trans-Hudson (PATH) tunnels beneath the Hudson River. PATH trains had transported commuters from Exchange Place Station on the New Jersey side of the Hudson to the WTC Station in the WTC underground complex. Exchange Place Station, which is approximately 6 meters lower in elevation than the WTC Station, was also flooded.

Water flooded the cable vault of the Verizon building at 140 West Street, where 70,000 copper pairs and additional fiber optic-lines had been severed by falling debris. Nearly 41,600 cubic meters of water had to be pumped from the vault during recovery. The seventh and ninth floors of the telecommunications building also sustained water damage.

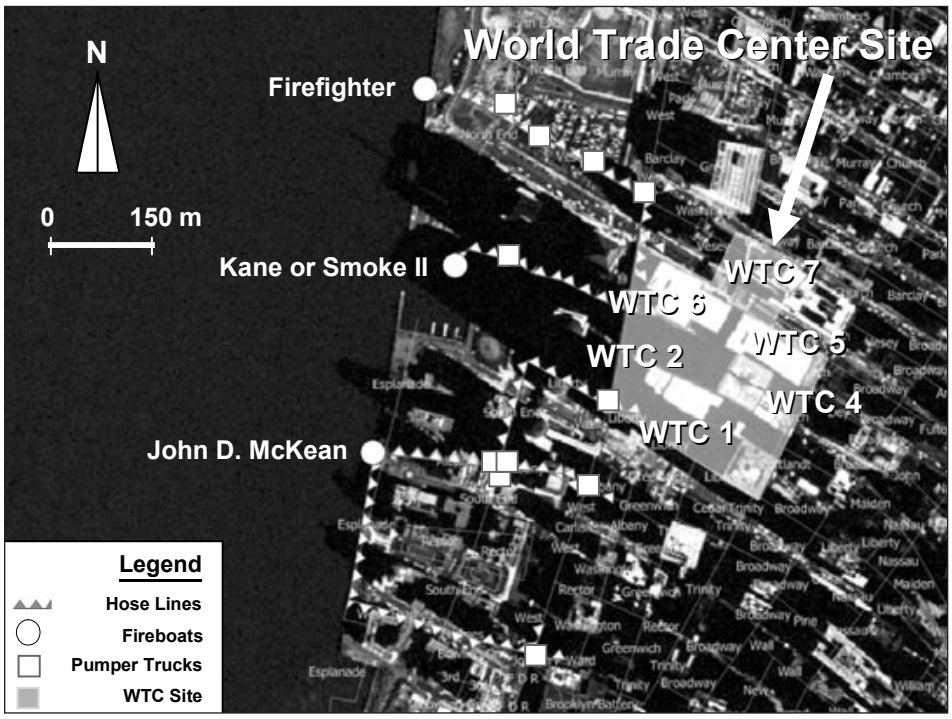

FIGURE 2 Aerial view of fireboat deployments in response to fires at the World Trade Center. Source: O'Rourke et al., 2005.

The capacity of the telecommunications office at 140 West Street had been one of the largest in the world. The building housed four digital switches, 500 optical-transport systems, 1,500 channel banks, 17,000 optical fiber lines, 4.4 million data circuits, and 90,000 message trunks. As a result of the damage and flooding, Verizon lost 200,000 voice lines, 100,000 private branch exchange lines, 4.4 million data circuits, and 11 cell sites. More than 14,000 business and 20,000 residential customers were affected.

The WTC disaster provides a graphic illustration of the interdependencies of

critical infrastructure systems. The building collapses triggered water-main breaks that flooded rail tunnels, a commuter station, and the vault containing all of the cables for one of the largest telecommunication nodes in the world. These included the Security Industry Data Network and the Security Industry Automation Corporation circuits used to execute and confirm block trades on the stock exchange. Before trading resumed on the New York Stock Exchange on Monday, September 17, 2001, the telecommunications network had to be reconfigured. Hence, ruptured water mains were linked directly with the interruption of securities trading and the restoration of international financial stability.

Resilience

Resilience is defined in *Webster's Unabridged Dictionary* as "the ability to bounce or spring back into shape, position, etc., after being pressed or stretched." Definitions vary slight, but they all link the concept of resilience to recovery after physical stress.

Since Hurricane Katrina, there has been a notable shift in emphasis from protecting critical infrastructure to ensuring that communities are resilient. When translating new ideas or concepts that connote a particular quality, such as resilience, into policy and implementation in the real world, we must remain mindful of the human dimensions of communities, which cannot be easily adapted or convolved into concepts based on the recovery of physical entities.

In addition, the concept of resilience, like the concept of critical infrastructure, is evolving. In its current form, the resilience of a community is an overarching attribute that reflects the degree of community preparedness and the ability to respond to and recover from a disaster. Because lifelines are intimately linked to the economic well-being, security, and social fabric of a community, the initial strength and rapid recovery of lifelines are closely related to community resilience.

Debate is likely to continue about the concept of resilience, and refinements and elaborations of the term are to be expected. Engineers and social scientists at the Multidisciplinary Center for Earthquake Engineering Research (MCEER) have proposed a framework for defining resilience (Bruneau and Reinhorn, 2007; Bruneau et al., 2003). According to Bruneau et al. (2003), resilience for both physical and social systems can be conceptualized as having four infrastructural qualities:

- Robustness: the inherent strength or resistance in a system to withstand external demands without degradation or loss of functionality.
- Redundancy: system properties that allow for alternate options, choices, and substitutions under stress.
- Resourcefulness: the capacity to mobilize needed resources and services in emergencies.
- Rapidity: the speed with which disruption can be overcome and safety, services, and financial stability restored.

As illustrated in Figure 3, an infrastructural quality, such as robustness, $Q(t)$, can be visualized as a percentage that changes with time. For buildings, $Q(t)$ may be the percentage of structural or functional integrity. For lifelines, $Q(t)$ may be the percentage of customers with water or electric power. Prior to a natural hazard, severe accident, or terrorist act, $Q(t)$ is at 100 percent. If the system is fully resilient, it remains at 100 percent. Total loss of service results in 0 percent $Q(t)$. If system disturbance occurs at time t_0, in response to an earthquake or hurricane, for example, damage to the infrastructure may reduce the quality to less than 100 percent. Level of service, as reflected by the robustness of the system, is a function of the probability and consequences of damage. Robustness is restored over time; at time t_1, the system is returned to its original capacity.

For a community, loss of resilience, R, can be measured as the expected loss in quality (probability of failure)

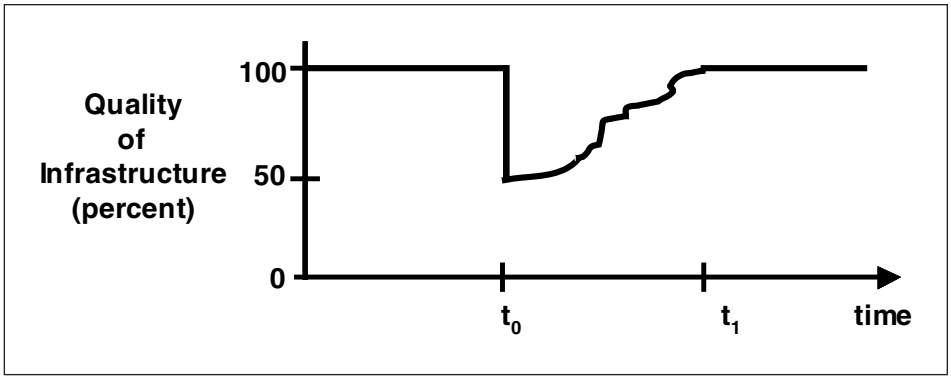

FIGURE 3 Measure of seismic resilience—conceptual definition. Source: Bruneau et al., 2003.

over the time to recovery, $t_1 - t_0$. Thus, mathematically, R is defined as:

$$R = \int_{t_0}^{t_1} [100 - Q(t)]dt$$

The resilience factor, R, is a simple measure for quantifying resilience. Additional mathematical developments of this concept addressing the probabilistic and multidimensional aspects of resilience are explained elsewhere (Bruneau and Reinhorn, 2007).

Figure 3 can be expanded to three and four dimensions to quantify the effects of resourcefulness and redundancy. The three-dimensional expansion, illustrated in Figure 4, has a third axis that quantifies the capacity to mobilize necessary resources and services in emergencies. As the level of activated resources increases, the time for recovery is reduced. In Figure 4, the initial loss of quality remains the same for purposes of illustration, but in a real event, mitigation activities and strengthening would raise the level of initial quality, and the metric for the loss of resilience, R, would be reduced.

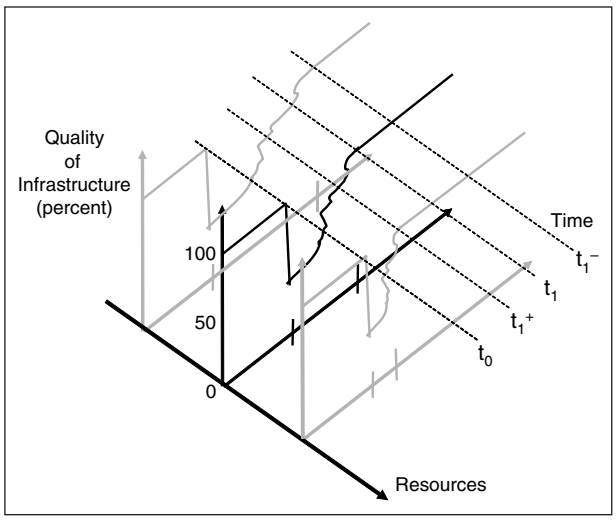

FIGURE 4 3-D resilience concept (expanded in resourcefulness dimension). Source: Bruneau and Reinhorn, 2007.

In some cases, a community may not return to pre-disaster levels after a major disaster. After Hurricane Katrina, for example, only about 40 percent of the original population had returned to Orleans and St. Bernard's parishes as of August 2006. If New Orleans does not recover to pre-Katrina levels, the resilience factor would not converge, reflecting the severity of Katrina's impact. If some restoration actually exceeds original quality levels, the definition of R would remain unchanged, and additional enhancements in quality would be assessed through related metrics.

The resilience framework also addresses the technical, organizational, social, and economic dimensions of infrastructure. Each intersection of the matrix in Table 1 has examples of technical, organizational, social, and economic activities that support the qualities of a resilient community. Robustness, for example, is considered in terms of technical dimensions, such as building codes and retrofitting procedures. Robustness is linked organizationally to emergency personnel and operations planning, and socially through the preparedness and vulnerability of different neighborhoods. Robustness is further related to the economic diversification in a given community or group of communities.

The Human Dimension

The human dimension of community resilience is expressed in the organizations responsible for lifeline systems and in the communities that receive services and resources from them. Community characteristics have a significant effect on resilience, especially the levels of vulnerability and preparedness. Average income, economic growth, level of awareness, and local politics, for example, have significant repercussions on critical infrastructure and disaster preparedness. These human factors set the stage for innovation and initiatives in building robust systems and implementing programs that can speed recovery.

Promoting Resilience

Resilience can be promoted in several ways: by awareness, leadership, resource allocation, and planning. Each of these is discussed briefly below.

Awareness

Resilience requires public concern about disasters and the operation of critical infrastructure, which, in turn, requires public education. Children can be educated effectively about hazards and environmental concerns at the K–8 level. The national network of some 350 science museums and centers can also help with education and outreach. These institutions are ideally suited to raising awareness of scientific and engineering issues with children, primarily at the K–8 level, and their families.

Public education also involves media coverage via newspapers and television. Thus journalists and news

TABLE 1 Matrix of Resilience Qualities with Examples Pertaining to the Technical, Organizational, Social, and Economic Dimensions of Infrastructure

Dimension/Quality	Technical	Organizational	Social	Economic
Robustness	Building codes and construction procedures for new and retrofitted structures	Emergency operations planning	Social vulnerability and degree of community preparedness	Extent of regional economic diversification
Redundancy	Capacity for technical substitutions and "work-arounds"	Alternate sites for managing disaster operations	Availability of housing options for disaster victims	Ability to substitute and conserve needed inputs
Resourcefulness	Availability of equipment and materials for restoration and repair	Capacity to improvise, innovate, and expand operations	Capacity to address human needs	Business and industry capacity to improvise
Rapidity	System downtime, restoration time	Time between impact and early recovery	Time to restore lifeline services	Time to regain capacity, lost revenue

Source: Kathleen Tierney, director of the Natural Hazards Center, University of Colorado at Boulder, personal communication.

reporters must understand the critical issues, which, in turn, requires that engineers and scientists be able to articulate principles and factual information clearly and effectively. Meaningful public education requires ongoing commitments by both the technical community and the media.

Risk communication is also important to public awareness. An example of effective risk communication is the naming of hurricanes, which identifies and personalizes the hazard. In this way, the danger is made tangible and transparent to people who might be in the path of destruction.

Local professional societies can also contribute significantly to risk communication. For example, the Earthquake Engineering Research Institute (EERI), an organization of professionals in engineering, the geosciences, and social sciences, regularly advocates seismic safety at the local and national levels. The Northern California Chapter of EERI conducted and participated in seminars, news conferences, and news events to promote seismic upgrades for the Bay Area Rapid Transit System (BART). EERI's efforts were instrumental in generating the votes to pass a $980 million bond issue for the seismic retrofitting of BART.

Leadership

Leadership is a critical factor in promoting resilient communities. Consider, for example, the actions of Mayor Eugene Schmitz of San Francisco, who presided over what is regarded as a corrupt and ineffective city government at the time of the 1906 earthquake. Schmitz ordered that looters in the aftermath of the earthquake be shot, thereby setting in motion "one of the most infamous and illegal orders ever issued by a civil authority in this country's history" (Fradkin, 2005). He also allowed the widespread dynamiting of buildings, which triggered fires that added to the conflagration that followed the earthquake. As a result, 490 blocks of the city burned to the ground, the worst single loss from fire in the United States.

Contrast Schmitz's actions with those of Mayor Rudolph Guiliani of New York City, who led a highly visible and effective response to the WTC disaster. Guiliani was able to galvanize emergency operations, despite the loss of the city's emergency operation center and the deaths of many fire chiefs and police personnel in the initial hours of the disaster.

Leadership is, perhaps, the most critical factor in promoting resilience, and also the least predictable. However, we know that effective leaders require good advice. Thus the engineering and scientific community must be prepared to communicate accurate, timely information to governmental officials.

Planning

Planning for emergencies requires drills and emergency-response exercises, which can reveal weaknesses and lead to improvements in operations. The plan that emerges from any particular exercise, however, is not as important as the planning process itself, because as soon as a disaster unfolds, the reality of the

event diverges from the features of even a meticulously designed scenario. With good planning, however, emergency managers and lifelines operators can improvise, and skilled improvisation enables emergency responders to adapt to field conditions.

Significant advances have been made in high-performance computational models that can simulate complex networks. These models put out highly graphic, detailed scenarios that enable modelers and associated emergency personnel to visualize a wide range of responses from an entire lifeline system to a specific part of that system.

Figure 5 is an example of complex simulations of the water-distribution network operated by the Los Angeles Department of Water and Power (LADWP) and its response to a scenario 6.9 magnitude earthquake on the Verdugo Fault in northeast Los Angeles. Figure 5a shows the peak velocity that would be experienced throughout the operating area. Figure 5b identifies functional and non-functional pipelines and pinpoints the locations where water demands cannot be satisfied.

This computer model, which was developed at Cornell University in collaboration with LADWP and MCEER, simulates all 12,000 kilometers of distribution and trunk pipelines and related facilities in the water-supply system. The model includes a special code that accounts for unstable flow in the damaged hydraulic network and is equipped with a library of 59 scenario earthquakes that can be simulated to enable study of water-supply performance in response to different seismic events. System performance can be assessed for a particular earthquake, or the seismic risk can be aggregated and evaluated for all 59 scenarios.

By running multiple scenarios, with and without modifications of the system, operators can identify recurrent patterns of response and develop an overview of potential performance, helping them plan for many eventualities and improving their ability to improvise and innovate in the event of a real temblor.

Resource Allocation

Constructing and sustaining critical infrastructure requires both adequate financial resources and a long-term commitment to finishing complex projects. Consider, for example, the New York City water supply, which is delivered by City Water Tunnel 1 (commissioned in 1917) and City Water Tunnel 2 (commissioned in 1938). The state of repair of these tunnels can only be inferred from indirect evidence because neither can be dewatered for inspection.

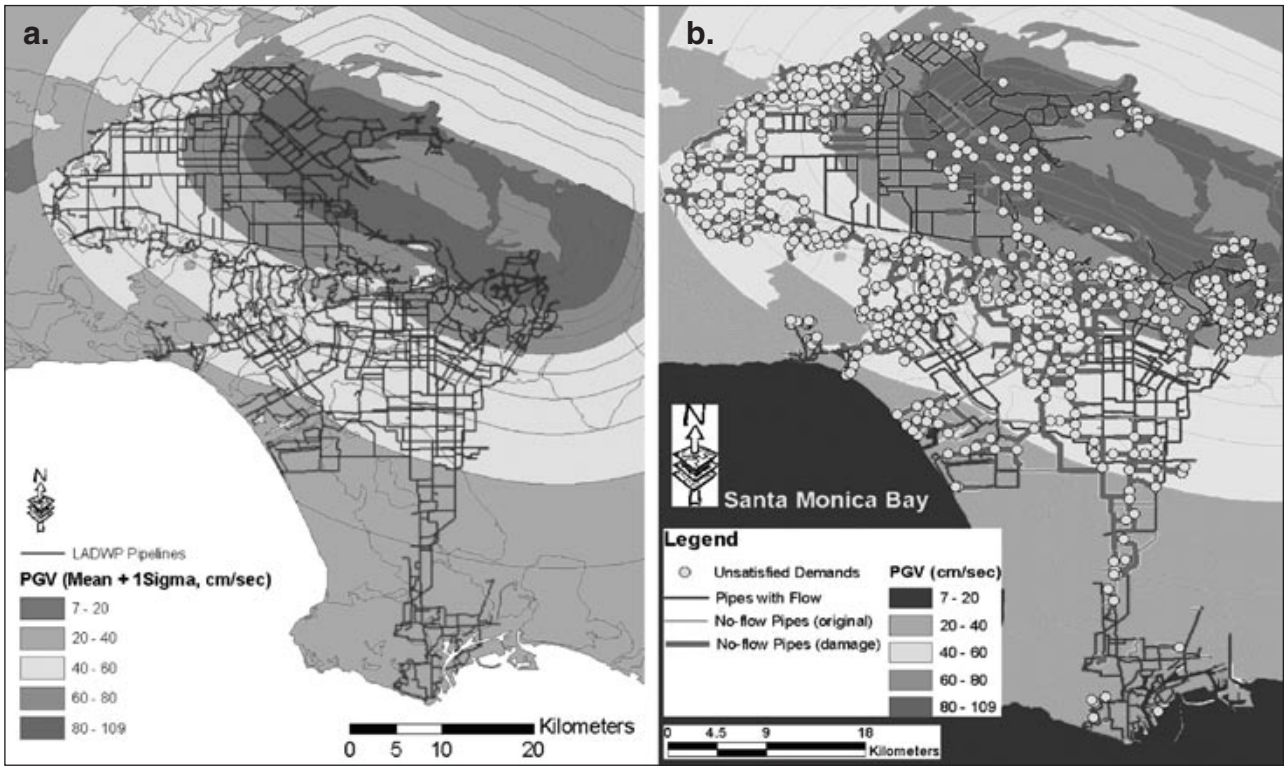

FIGURE 5 Simulation of Los Angeles water-supply response to magnitude 6.9 scenario earthquake. a. Strong ground motions. b. Water-supply response.

A third water tunnel is crucial to providing an alternative path so that each of the first two tunnels can be taken out of service, inspected, and repaired. In fact, no project is more critical to the well-being and security of New York City.

The construction of City Water Tunnel 3 began in 1970 and is scheduled for completion in 2020 at an estimated total cost of $6 billion. The new tunnel will require nearly 100 kilometers of tunneling over a period of five decades. This project is indicative of the size, financial requirements, and time frame associated with many critical infrastructure projects.

Conclusion

Developing resilient communities with appropriate critical infrastructure requires awareness through education and risk communication, strong, innovative leadership, effective planning, and the long-term commitment of resources to put complex systems into place. At first glance, these requirements do not appear to be directly associated with engineering and technology. However, all of them must be informed by accurate, up-to-date science, technology, and information made possible by partnerships and networks among communities, governments, and scientists and engineers.

Acknowledgments

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Governments must understand the resiliency and risk management strategies of private-sector enterprises.

Building a Resilient Organization

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Yossi Sheffi

The 9/11 attack, the SARS epidemic, Hurricane Katrina, and scores of other disruptions have made companies more aware of the need for active risk management. Governments in the West have also realized that more than 85 percent of the infrastructure in western countries is owned and/or operated by the private sector. At the very least, this means that governments need to understand the resiliency and risk management strategies of private-sector enterprises. This article, based on ideas described in my recent book, *The Resilient Enterprise: Overcoming Vulnerability for Competitive Advantage* (MIT Press, 2005), outlines some of the ways companies prepare for inevitable large disruptions. Most of the lessons are also relevant to government, nonprofit, and other types of organizations.

A Fire in the Desert

On Friday night, March 17, 2000, in Albuquerque, New Mexico, a bolt of lightning struck a factory of Philips NV, the Dutch electronics conglomerate, causing the furnace in Fabricator No. 22 to catch fire. At the time, this did not seem to be a major event. The automatic sprinkler systems were activated, and Philips-trained staffers put out the fire in less than 10 minutes. Thus, by the time firefighters from Albuquerque arrived, they had nothing to do but verify that the plant was safe. What the firefighters did not realize was that the location of the fire had been one of the cleanest places on earth,

a semiconductor fabrication plant, or "fab," for making special chips for cell phones. The fire had damaged two of the four clean rooms.

Philips immediately notified the two largest customers of the plant—Ericsson LM and Nokia Corporation—both of whom were in the process of launching a new generation of cell phone based on chips produced in the Albuquerque plant. In the original message, Philips estimated a one-week delay in the supply of chips. Nokia was not unduly perturbed by the news, but just to be sure, placed the affected chip on a "special watch" that called for daily discussions between Nokia and Philips engineers. Nokia discovered very quickly, however, that it would take several months to bring the Albuquerque plant back to full production, causing the company to miss the launch of its new-generation cell phones. At that point, Nokia sprang into action on two fronts. First, it pressed Philips to find an alternative supply from its other fabs around the world—even though this would mean outsourcing some of Philips' own production. Second, Nokia looked for alternative suppliers around the world and paid them extra for quick setup and testing and expedited production.

Ericsson, Philips' other major customer, basically ignored Philips' original message, knowing that one-week delays in supply chains are routine and that the company had enough stock to cover the gap. In sharp contrast to Nokia, however, Ericsson did not detect the problem fast enough, and by the time the magnitude of the shortage became apparent, the worldwide supply of special chips had been sewn up by Nokia. At the end of 2000, Ericsson announced a staggering 16.2 billion kronor (U.S. $2.34 billion) loss in the company's mobile phone division, which the company blamed on a slew of component shortages (LaTour, 2001). About a year after the fire, Ericsson retreated from the handset production market. In April 2001, Ericsson signed a deal with Sony to create a joint venture to design, manufacture, and market handsets. The new company, Sony-Ericsson, would be owned 50–50 by the two companies.[1] Thus one of Nokia's major competitors was eliminated from the marketplace. Within six months of the fire, Nokia's year-over-year share of the handset market increased from 27 to 30 percent.

[1] On January 26, 2001, Ericsson announced that it would no longer manufacture handsets and outsourced all of its manufacturing to Flextronics Inc. The Sony joint venture was announced three months later (Williams, 2001).

Although both Ericsson and Nokia had been hit by the same disruption, one recovered while the other had to give up significant parts of its business. How could this happen? Why did the same disruption cause one large, sophisticated company to exit the market and the other to increase its market share?

This example illustrates many lessons of resiliency. Most important, risk management is not a company issue that can be handled "within the four walls." It is a supply chain management issue. Every company is a "citizen" of its supply chain that depends on networks of suppliers, logistics providers, brokers, port operators, and many other facilitators to get parts to plants and distribute products to customers. A serious business interruption can happen, not only because one of the company's own facilities, distribution channels, or workforce is disrupted, but also when an element in its supply chain, its ecosystem, is disrupted. Repairing the damage to the Philips plant cost about $40 million, mostly covered by insurance. The damage to Ericsson—the loss of its handset manufacturing business—was orders of magnitude larger.

Risk management is a supply chain issue, not a company issue.

The Nature of Risk

Most corporations today approach risk management in one of two ways: (1) based on models and numbers or (2) based on subjective beliefs about the future. If there is reason to believe that the patterns of the past will be repeated, a company can use data, probability distributions, and models to forecast future patterns. These forecasts can then be used as a basis for strategies to address expected variations in future outcomes. However, other outcomes, known as high-impact, low-probability (HILP) events, are difficult to forecast because they are outside the company's past experience. For the same reason, HILP events can have a significant impact on an enterprise.

Most companies first classify possible risks along two axes (Figure 1). One axis denotes the likelihood of a particular disruption; the other axis denotes the impact (or

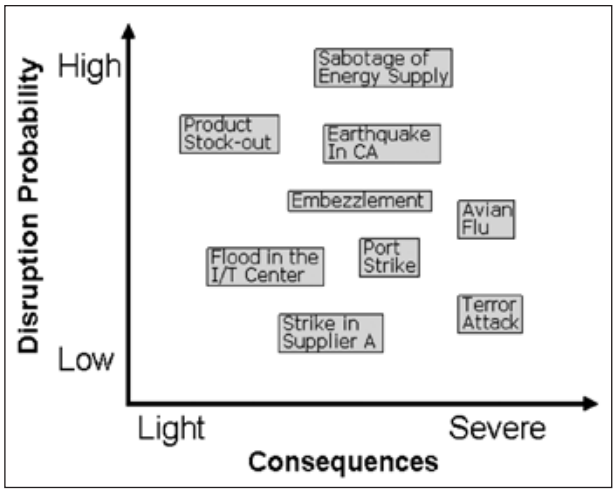

FIGURE 1 Example of classification of threats.

severity) of this disruption once it hits. Figure 1 shows a simple example of this kind of risk classification. The space in which threats are placed can then be divided into four quadrants, as depicted in Figure 2. Rare, insignificant events are placed in the lower left-hand quadrant and are not of concern. Events with high probability and light consequences are also of little concern because data, statistical distributions, and models provide ample warnings and tools to address them. These so-called "firefighting" events that operations managers deal with all the time are placed in the upper left quadrant.

Even high-probability, high-impact events (upper right quadrant) are not of particular concern, because special groups in each company have processes in place for dealing with them. For example, BP suffers substantial losses every time a hurricane moves through the Gulf of Mexico. Deep-water platforms have to be buttoned down and evacuated, and platforms are often damaged and have to be repaired at very high cost. However, because hurricanes in the Gulf of Mexico are an annual phenomenon, BP has a well developed process for dealing with them.

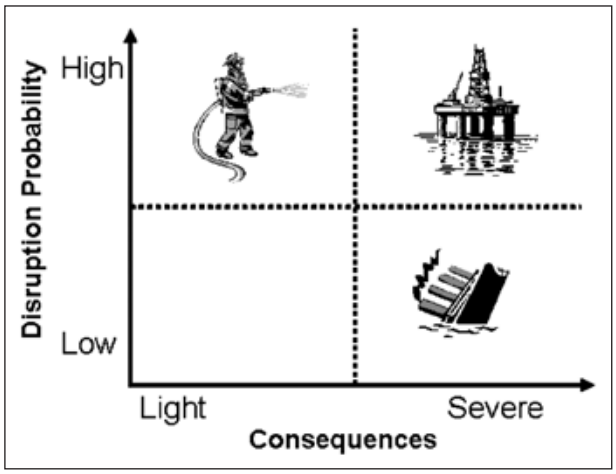

FIGURE 2 Four quadrants of risks.

HILP events, however, such as the sinking of the *Titanic*, shown in the lower right quadrant, are qualitatively different. These are events that companies, or governments, have not imagined and are not prepared for and that, therefore, can have devastating consequences. Examples include the 1984 disaster in the Union Carbide plant in Bhopal, India, the 1986 Chernobyl nuclear accident, the 2003 SARS outbreak, the 9/11 terrorist attack, and Hurricane Katrina in 2005.

Note that the expected damage (i.e., the product of probability and consequences) is not a good measure of risk! Frequent small disruptions have little in common with rare, high-impact disruptions, even though their expected values may be similar. The former are dealt with by operations managers in the course of their jobs, while the latter can devastate an enterprise. And disruptions with the highest expected value (high-probability, high-impact events) should not be the focus of most attention from risk managers because organizations are most likely ready for them and have processes in place to detect them and deal with their consequences.

Government Responses to High-Impact, Low-Probability Events

In many cases, HILP events cause fear and confusion, and governments may feel compelled to act quickly, even before all of the necessary information is available. Unfortunately, hasty government actions often exacerbate problems.

After the September 11 terrorist attacks, for example, the U.S. government closed U.S. borders and shut down all flights in and out of the country. These measures had immediate impacts on many supply lines. Ford Motor Company had to idle several assembly lines intermittently because trucks loaded with components coming in from Canada and Mexico were delayed. As a result, Ford's fourth-quarter output in 2001 was down 13 percent compared to its production plan (Andel, 2002). In response to the 2001 outbreak of foot and mouth disease, the British government not only slaughtered 6.5 million cows, pigs, and sheep, but also closed the countryside to tourists. Damage to the tourism industry turned out to be significantly greater than damage to

the agricultural industry—and it was clearly caused by the government's actions.

Thus enterprise managers must consider the consequences of possible government actions as part of any disruption scenario. For example, if a container explodes in a U.S. port, the government is likely to close all ports, thus causing significant economic damage.

The High Likelihood of Low-Probability Events

On Thursday, May 8, 2003, a powerful tornado hit the General Motors (GM) assembly plant in Oklahoma City causing extensive damage and a second-quarter charge of $140 to $200 million. Although the probability that a specific disruption will hit a given element in a company's supply chain during a particular week is negligible, the probability that a major disruption of some type will take place somewhere in GM's vast supply chain sometime during a given year is significant. Thus an enterprise like GM must be resilient.

Resilience is, literally, the ability of a material to return to its former shape after a deformation. Similarly, a resilient enterprise is an organization that can "bounce back" to its pre-disruption level of manufacturing, service to customers, or any other relevant performance metric. Enterprises can build in resiliency in two ways— through redundancy and through flexibility. Regardless of the general strategy, however, early detection of a disruption and the right corporate culture are major determinants of resilience.

Early Detection

Among many counterterrorism professionals, the real nightmare scenario is not a nuclear explosion or a "dirty" bomb, but an attack in which an organization does not realize it is under attack until it is too late. For example, the first symptoms from a lethal biological agent may not be evident for weeks, but then might spread very quickly. Therefore, the Centers for Disease Control in the United States, on a daily basis, looks into geographical clusters of respiratory infections and small rashes accompanied by fever, symptoms that may signal a bio-terror attack in progress (Gerberding, 2004).

At the time this article is being written, the World Health Organization and local health authorities are spending significant resources to detect the onset of avian flu. If the virus mutates so it can be transmitted among humans, it could be even deadlier than the 1918 Spanish flu, which reportedly killed 30 to 60 million people worldwide. The best defense against pandemics is early detection and quarantine until antiviral drugs and vaccines against the active flu strain can be developed.

In many cases, early detection of a disruption means not only that an organization receives warning signs, but also that it can process, understand, and act on those signals. A clear failure of organizational response took place during Hurricane Katrina. The city of New Orleans started the evacuation too late, the state of Louisiana called in Pentagon resources too late, and the Federal Emergency Management Administration provided a meager response at best. And this was a disaster the country was warned about days in advance.

Enterprises can build in resiliency through redundancy or through flexibility.

Redundancy in Supply Chains

An enterprise can be resilient if it creates redundancies throughout its supply chain—low-capacity utilization, extra inventory, multiple suppliers for the same part, and so on. For example, the U.S. Postal Service (USPS) was able to withstand the anthrax attacks very well, even though several major facilities had to be shut down. Over the last two decades, as fax, e-mail, and online payments had reduced the volume of mail, USPS had not adjusted its capacity at the same pace. Thus it had a built-in redundancy that proved useful in that situation. However, very few commercial enterprises can afford redundant capacity that can be activated in case of a disruption.

The most common type of redundancy is a safety stock of parts and finished products, which most companies maintain to protect themselves against "normal," day-to-day fluctuations in the global flow of commerce. However, maintaining safety stock as protection against HILP events is very expensive because a lot of inventory would have to be kept for a long time. Keeping a large inventory is expensive for two reasons: (1) it has to be maintained, financed, warehoused, and attended to, even as the value of the product may decrease while it is kept in inventory; and (2) excess inventory leads to sloppy operations—if there is a defective part in the manufacturing process or a defective product ready

to ship, it is easy for managers to "take one from the inventory pile" rather than take the time immediately to investigate and correct the problem. As the Toyota manufacturing system has proven, fixing problems at the source is an essential part of a superior business model.

In the last two decades, leading manufacturers, distributors, and retailers worldwide have made tremendous strides in developing "lean," tightly coupled, efficient supply chains that can react to disruptions quickly based on advanced information technology applications, electronic data interchange standards, and finely honed processes. Nevertheless, the lack of built-in redundancy makes even these supply chains vulnerable to disruptions. At the same time, no company can afford significant redundancies, which are likely to reduce competitiveness in the marketplace.

Fixing problems at the source is essential to superior business models.

Flexibility

If companies cannot afford to "fatten" their operations with redundancies, they must build in flexibility. Unlike redundancy, increasing supply-chain flexibility can help a company not only withstand significant disruptions but also respond to demand fluctuations, thus increasing its competitiveness. The notion of flexibility is based on interchangeability—the ability to interchange elements in a supply network quickly.

Standardized Facilities and Processes

Intel plants around the world are identical (following their *Copy Exact!* philosophy). When the SARS epidemic hit Southeast Asia, Intel was able to move production from its Indonesian plant to other plants with relative ease. Similarly, when a severe ice storm shut down the main UPS air hub in Louisville, Kentucky, in 1986, making it impossible for workers to reach the facility, the company kept operating by flying in workers from other parts of its system. Since UPS uses standard terminal design and processes throughout its vast system, the new workers were able to keep the Louisville hub operating.

Interchangeable Parts and Products

If the same parts are used in different products, the inventory of these parts is less susceptible to changes in the demand for those products. For example, if a product with a given part cannot be manufactured because of an unrelated problem, the part can still be used in other products and does not have to be discarded or held in stock for a long time. Following this logic, Intel has reduced a mix of 2,000 different types of resistors, capacitors, and diodes to only 35 types (Anderson, 2004). For the same reason, Southwest Airlines uses only one type of airplane—the Boeing 737. Airlines are always subject to disruptions from bad weather, crew shortages, airport congestion, and so on. However, because every Southwest crew can fly every company aircraft, Southwest has the flexibility to respond to disruptions faster than other airlines.

Concurrent Processes

Overlapping sequential processes can not only speed up the recovery phase after a disruption, but can also lead to improved market responses. Lucent Technologies achieves concurrency through a single supply-chain organization that spans multiple company functions, including engineering and sales. By aligning these activities under the supply-chain umbrella, the company can view operational areas concurrently and quickly assess their status in an emergency. In addition, the company's responses to emergencies are faster and more efficient because people in different organizational units are accustomed to working together.

Postponement

Designing products and processes for late value addition and late customization offers another layer of flexibility. By keeping products in a semifinished form, a company can move its products from surplus to deficit areas. This strategy also increases fill rates and improves customer service without increasing inventory carrying costs because products can be completed to meet a particular customer's needs. Italian clothing manufacturer and retailer Benetton, for example, redesigned its manufacturing processes so that products that are subject to extreme variability in the demand for color are produced as generic, undyed items that can be finished when customer preferences can be determined, sometimes even after orders are placed.

Alignment of Procurement Strategy with Supplier Relationships

In response to 9/11 and other disruptions, some observers advised companies to maintain multiple suppliers for essential parts. However, there may be very good business reasons for having a single supplier, even for some critical parts: (1) a single supplier is more likely to allow access to its innovation because it is less worried about "seepage" of its intellectual property to a competing supplier; (2) the fixed, per-supplier, cost of procurement is minimized; (3) the company can concentrate its buying power, possibly leading to lower purchase costs; and (4) a company becomes a more significant customer of the supplier, thereby getting more attention.

But when using a single supplier, an enterprise does put all of its eggs in a single proverbial basket. To manage the related risk, the enterprise must commit to deep relationships with the single supplier—it must have a detailed understanding, and continuously monitor, the supplier's strategy, financial condition, and the supplier's suppliers. This strategy is shown in the top left-hand quadrant of Figure 3. If a company decides not to incur the cost of developing deep relationships with suppliers, it will be less knowledgeable about its trading partners and, therefore, less likely to be forewarned of supply problems. In this case, the enterprise must spread its risk by maintaining a network of suppliers (lower right quadrant in Figure 3).

Each company must choose the approach that aligns its corporate-supplier relationships with its procurement strategy. For example, when Land Rover's sole supplier of chassis for the Discovery vehicle went bankrupt unexpectedly in December 2001, the company almost lost its business. Because of inadequate monitoring, Land Rover was totally unprepared for the bankruptcy and eventually had to pay off some of the supplier's debt. This is the dangerous situation shown in the lower left quadrant of Figure 3. Maintaining close relationships with many suppliers may simply be too expensive to be practical.

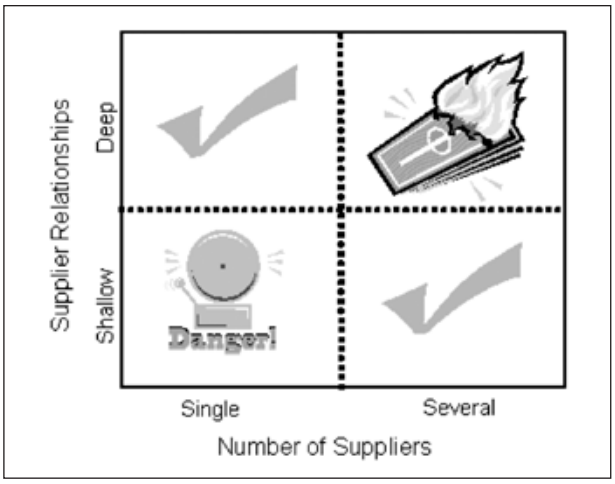

FIGURE 3 Alignment of procurement strategy with number of suppliers.

Collaboration

By developing close, collaborative relationships with trading partners, companies can become allies during a crisis. Toyota, for example, recovered very quickly, with the help of dozens of suppliers, from a fire that gutted the sole plant of its main P-valve supplier in February 1997 (Nishiguchi and Beaudet, 1998). In another case, loyal customers enabled bond trader Cantor Fitzgerald to recover after it lost more than a third of its employees and its headquarters on 9/11. Collaborative relationships can also be crucial to companies responding to fluctuations in demand, which may require that the entire supply chain ramp production up or down.

Corporate Culture

The factor that clearly distinguishes companies that bounce back from disruptions quickly, and even profit from them, is their corporate culture. Corporate culture is difficult to define and even more difficult to change. But as the success of the quality movement in the 1980s showed, cultural change can become "everybody's" issue, rather than the exclusive domain of experts or vested interests. Resilient organizations, such as Nokia, Toyota, UPS, Dell, and the U.S. Coast Guard, may not appear to have much in common, but a closer look shows that they have several common traits.

Continuous Communication among Informed Employees

Resilient companies communicate obsessively, keeping all managers aware of strategic goals, tactical factors, and the day-by-day, even minute-by-minute, pulse of the business. Dell employees, for example, have continuous access to product manufacturing and shipment information, as well as to the company's overall status. Thus, when disruptions occur, employees can react based on up-to-date knowledge, even if the normal lines of communication have broken down.

Distributed Power

In addition to continuous communications and informed employees, resilient organizations empower

teams and individuals to take drastic action when necessary, without waiting for the usual approvals. Toyota assembly-line workers can halt production by pulling an alarm cord, which brings in a team of engineers to fix the problem. The Coast Guard moved assets into Louisiana before Katrina hit and was operating life-saving, round-the-clock missions without specific instructions from the U.S. Department of Homeland Security or even from its national headquarters in Washington, D.C. The Coast Guard was guided by an operating principle called "On Scene Initiative," which essentially empowers local commanders (USCG, 2006). In all of these organizations, individuals who take action are celebrated when they are right but not punished when they are wrong.

Passion for Work

Successful companies engender a sense of the "greater good" in their employees. As a Southwest Airline executive explained, "The important thing is to take the bricklayer and make him understand that he's building a home, not just laying bricks." Similarly, navy sailors do not think of their job as driving big ships, but rather as defending freedom.

Conditioning for Disruptions

Through frequent and continuous "small" operational interruptions, resilient, flexible organizations are conditioned to be innovative and flexible when HILP events occur. UPS operations, for example, are subject to adverse weather conditions, traffic congestion, road closures, and many other delays. Thus the company's recovery processes are tested daily.

Companies with relatively predictable environments can interject uncertainty for training purposes. A special Intel team, for example, routinely visits plants and introduces simulated disruptions, such as the failure of a critical supplier. The team runs the plant through a complete drill of finding and qualifying alternative suppliers, arranging transportation, changing production schedules, and so on, just to guard against managerial complacency.

Conclusion

A resilient organization is not only "hardened" to withstand disruptions of all kinds, but is also more competitive on a day-to-day basis. Supply disruptions create shortages, similar to spikes in demand caused by supply/demand imbalances, and resilient enterprises can react to changing market demand ahead of their competitors. Furthermore, resilient enterprises can consider disruptions to be opportunities rather than problems. When large-scale disruptions affect a whole industry or an entire region, resilient enterprises are likely to bounce back ahead of their competition, winning market share and increasing customer loyalty.

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NAE News and Notes

Class of 2007 Elected

In February, NAE elected 64 new members and 9 new foreign associates, bringing the number of U.S. members to 2,217 and the number of foreign associates to 188. Election to NAE, one of the highest professional distinctions accorded to an engineer, honors those who have made outstanding contributions to "engineering research, practice, or education, including . . . significant contributions to the engineering literature" and to "new and developing fields of technology, . . . major advancements in traditional fields of engineering, or . . . innovative approaches to engineering education." A list of the newly elected members and foreign associates follows, with primary affiliations at the time of election and brief descriptions of principal accomplishments.

New Members

Asad Ali Abidi, professor, Electrical Engineering Department, University of California, Los Angeles. For contributions to the development of integrated circuits for MOS RF communications.

Edward C. Aldridge Jr., retired president and chief executive officer, The Aerospace Corporation, El Segundo, California. For leadership in the development and application of advanced technologies for space and command and control systems.

Nicolaos G. Alexopoulos, dean of engineering, University of California, Irvine. For contributions to microwave circuits, antennas, and structures for low observable technologies, and for contributions in engineering education.

George E. Apostolakis, professor of nuclear science and engineering, Massachusetts Institute of Technology, Cambridge. For innovations in the theory and practice of probabilistic risk assessment and risk management.

Peter Michael Asbeck, professor of electrical and computer engineering, University of California, San Diego. For contributions to heterojunction bipolar transistor and integrated circuit technology.

Rudolph Bonaparte, president and chief executive officer, GeoSyntec Consultants, Atlanta, Georgia. For contributions to geoengineering with geosynthetics, the design of landfill waste-containment systems, and leadership in geotechnical engineering practice.

Eric A. Brewer, professor, Computer Science Division, University of California, Berkeley. For the design of highly scalable Internet services.

William R. Brody, president, Johns Hopkins University, Baltimore, Maryland. For contributions to digital radiography, and for leadership in engineering at the interface between academia and industry.

Dale Edward Burton, sector vice president, technology, and chief technology officer, integrated systems, Northrop Grumman Corporation, Melbourne, Florida. For innovations and leadership in the development, testing, and fielding of the Joint STARS System.

Stuart K. Card, senior research fellow, Palo Alto Research Center (PARC), Palo Alto California. For establishing models of human-computer interaction.

Edwin A. Chandross, consultant, Materials Chemistry LLC, Murray Hill, New Jersey. For innovation and leadership in the design and development of optical materials related to electronics and communications.

Stephen Y. Chou, Joseph C. Elgin Professor of Electrical Engineering, Princeton University, Princeton, New Jersey. For contributions to nanoscale patterning and to the scaling of electronic, photonic, magnetic, and biological devices.

George R. Cotter, director for information technology and chief information officer, National Security Agency, Fort Meade, Maryland. For leadership in the research and development of high-end computing and communications for national security.

Harold Gene Craighead, C.W. Lake Jr. Professor of Engineering, Cornell University, Ithaca, New York. For contributions to the fabrication and exploitation of nanostructures for electronic, optical, mechanical, and biological applications.

John J. Dorning, Whitney Stone Professor of Nuclear Science and Engineering, professor of engineering physics, and professor of applied mathematics, University of Virginia, Charlottesville. For the development of advanced computational methods for nuclear reactor analysis.

Charles T. Driscoll, University Professor of Civil and Environmental Engineering, Syracuse University, Syracuse, New York. For leadership in understanding the ecological impact of acid rain and mercury depositions.

Shun Chong Fung, retired senior research associate, ExxonMobil Research and Engineering Company, Bridgewater, New Jersey. For the investigation of factors underlying the deactivation and reactivation of catalysts, and for application of the findings in commercial practice.

Bruce C. Gates, Distinguished Professor of Chemical Engineering, University of California, Davis. For scholarship on catalysis, innovative research on hydroprocessing and supported molecular catalysts, and exemplary leadership in collaborative university/industry research.

Robert M. Gray, Lucent Technologies Professor in Communications and Networking, Stanford University, Stanford, California. For contributions to information theory and data compression.

Karl A. Gschneidner Jr., Anson Marston Distinguished Professor, Department of Materials Science and Engineering, Iowa State University, Ames. For contributions to the science and technology of rare-earth materials.

John O. Hallquist, president, Livermore Software Technology Corporation, Livermore, California. For the development of explicit nonlinear finite element methods and their worldwide dissemination in the DYNA family of programs.

Leroy E. Hood, president, Institute for Systems Biology, Seattle, Washington. For the invention and commercialization of key instruments, notably the automated DNA sequencer, that have enabled the biotechnology revolution.

Paul M. Horn, senior vice president, research, IBM Corporation, Yorktown Heights, New York. For leadership in the development of information technology products, ranging from microelectronics to supercomputing.

Larry J. Hornbeck, TI Fellow, Texas Instruments Inc., Plano, Texas. For the invention and development of the digital micromirror device (DMD) and its application to projection display technology.

Mark A. Horowitz, professor of electrical engineering and computer science, Stanford University, Stanford, California. For leadership in high-bandwidth memory-interface technology and in scalable cache-coherent multiprocessor architectures.

William A. Hustrulid, independent consultant, Bonita Springs, Florida. For contributions to the theory and practice of geomechanics in the design of safe and efficient underground mining systems.

Stuart Dodge Jessup, senior research scientist, Carderock Division, Navy Surface Warfare Center, West Bethesda, Maryland. For the theory, design, and development of low-noise propellers to improve the survivability of U.S. Navy ships.

Paul John Kern, general (retired), U.S. Army, Reedville, Virginia. For bringing modern digitization technology to bear on military effectiveness, training, and procurement.

Timothy Laurence Killeen, director, National Center for Atmospheric Research, Boulder, Colorado. For contributions to interferometer design, and to measurement and modeling of the properties and dynamics of the upper atmosphere and ionosphere.

James L. Kirtley Jr., professor of electrical engineering and computer science, Massachusetts Institute of Technology, Cambridge. For contributions to the theoretical analysis, design, and construction of high-performance rotating electric machinery.

Charles T. Kresge, vice president for research and development, Dow Chemical Company, Midland, Michigan. For contributions to the rational design and engineering of mesoporous inorganic materials.

Panganamala R. Kumar, Franklin W. Woeltge Professor of Electrical and Computer Engineering, University of Illinois, Urbana-Champaign. For contributions to adaptive control, manufacturing systems, and wireless networks.

Stelios K. Kyriakides, Temple Foundation Endowed Professor, Department of Aerospace Engineering and Engineering Mechanics, University of Texas, Austin. For contributions to the understanding and technological applications of propagating instability phenomena in structures and materials.

Simon S. Lam, Regents Chair in Computer Sciences, University of Texas, Austin. For contributions to computer network protocols and network security services.

Ann L. Lee, vice president, process development, Genentech Inc., South San Francisco, California. For innovation and development of the large-scale, cost-effective production of vaccines that have saved lives worldwide.

David B. Marshall, principal scientist, Rockwell Scientific Company, Thousand Oaks, California. For contributions that have led to improved strength, toughness, environmental stability, and reliability of structural ceramics and composites.

Robin K. McGuire, president and principal, Risk Engineering Inc., Boulder, Colorado. For advances in engineering applications of probabilistic risk assessment in earthquakes and other natural hazards.

Teresa H. Meng, Reid Weaver Dennis Professor of Electrical Engineering, Stanford University, Stanford, California. For pioneering the development of distributed wireless network technology.

Silvio Micali, professor, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge. For contributions to modern cryptography, through the development of zero-knowledge protocols and the theory of pseudo-randomness.

J S. Moore, Admiral B.R. Inman Centennial Chair in Computing Theory, University of Texas, Austin. For contributions to automated reasoning about computing systems.

John W. Morris Jr., professor of metallurgy, materials science, and mineral engineering, University of California, Berkeley. For advancing our understanding of the strength and toughness of materials through microstructural manipulation.

David J. Nash, president, BE&K Inc., Birmingham, Alabama. For leadership in the reconstruction of devastated areas after conflicts and natural disasters.

Martin E. Newell, Adobe Fellow, Adobe Systems Inc., San Jose, California. For contributions to computer-graphics modeling, rendering, and printing.

Robert E. Nickell, president, Applied Science & Technology, San Diego, California. For contributions to the finite element method and the safe operation of power plants.

Syd S. Peng, Charles E. Lawall Chair in Mining Engineering, West Virginia University, Morgantown. For leadership in the development of advanced longwall-mining and ground-subsidence-control technologies.

William P. Pierskalla, Distinguished Professor Emeritus and Dean Emeritus, University of California, Los Angeles. For leadership in the development and application of operations research tools to make health care more effective.

Gintaras V. Reklaitis, Edward W. Comings Professor of Chemical Engineering, Purdue University, West Lafayette, Indiana. For developing the theory and application of batch design, scheduling, and optimization tools, and for outstanding contributions to education.

Walter Jeremiah (Jerry) Sanders III, retired chairman, Advanced Micro Devices Inc., Sunnyvale, California. For leadership in product development and manufacturing in the semiconductor industry.

James F. Stahl, chief engineer and general manager, County Sanitation Districts of Los Angeles County, Whittier, California. For leadership in public health and environmental protection in the wastewater utility industry.

Thomas G. Stephens, group vice president, General Motors Powertrain, General Motors Corporation, Pontiac, Michigan. For leadership in the development of advanced automotive power trains with improved performance, fuel efficiency, and lower emissions.

Kenneth E. Stinson, chairman and chief executive officer, Peter Kiewit Sons' Inc., Omaha, Nebraska. For leadership in the design-build engineering and construction contracting of large public works projects.

Eva Tardos, professor, Department of Computer Science, Cornell University, Ithaca, New York. For contributions to the design and analysis of efficient algorithms for solving network problems.

Sebastian Thrun, associate professor of computer science and electrical engineering, Stanford University, Stanford, California. For contributions to probabilistic robotics, including mobile robot localization and mapping.

Lloyd N. Trefethen, professor of numerical analysis, Oxford University, Oxford, England. For contributions to stability theory in numerical analysis and its application to determining the onset of turbulence.

James J. Truchard, president, chief executive officer, and founder, National Instruments Inc., Austin, Texas. For creating "virtual instrumentation," which enabled the rapid development of customized measurement systems in industry, academia, and classrooms.

John N. Tsitsiklis, professor, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge. For contributions to the theory and application of optimization in dynamic and distributed systems.

Jonathan S. Turner, Barbara J. and Jerome R. Cox Jr. Professor of Computer Science, Washington University, St. Louis, Missouri. For contributions to the design and analysis of high-performance communication networks.

Sergio Verdú, professor of electrical engineering, Princeton University, Princeton, New Jersey. For contributions to multiuser communications and information theory.

Anil V. Virkar, professor of materials science and engineering and chair, Department of Materials

Science and Engineering, University of Utah, Salt Lake City. For contributions to the development of high-temperature ionic and electronic materials for fuel cells and batteries.

David A. Whelan, vice president-general manager and deputy of Boeing Phantom Works, Boeing Company, Seal Beach, California. For contributions to and leadership in the field of radar imaging and its application to stealth aircraft.

Paul K. Wright, A. Martin Berlin Chair in Mechanical Engineering, University of California, Berkeley. For the invention of the first open-architecture control of manufacturing systems, and for development of Internet-based CAD/CAM systems.

James Clair Wyant, dean, College of Optical Sciences, University of Arizona, Tucson. For the development of interferometric optical measurement techniques with nanometer precision for use in production environments.

Adrian Zaccaria, vice chairman, president, and chief operating officer, Bechtel Group Inc., San Francisco, California. For leadership in the design, construction, and maintenance of power plants and other types of engineering facilities all over the world.

Charles F. Zukoski, professor of chemical engineering and vice chancellor for research, University of Illinois, Urbana-Champaign. For research on the manipulation of particle interactions to alter their suspension properties, and for leadership in education.

New Foreign Associates

Timothy Berners-Lee, senior research scientist, Massachusetts Institute of Technology, Cambridge. For development of the World Wide Web.

Roy Billinton, Emeritus Professor, Department of Electrical Engineering, University of Saskatchewan, Saskatoon, Canada. For contributions to teaching, research, and application of reliability engineering in electric power generation, transmission, and distribution systems.

Avelino Corma, director, Instituto de Tecnología Química, UPV-CSIC, Valencia, Spain. For contributions to the understanding of heterogeneous catalysis that led to numerous commercialized solid catalysts used worldwide.

Joachim Heinzl, president, Bayerische Forschungsstiftung, Technische Universität München, Germany. For contributions to the worldwide introduction and use of drop-on-demand ink-jet printers.

Kenichi Iga, executive director, Japan Society for the Promotion of Science, Tokyo. For contributions to advanced optoelectronics, including the vertical-cavity surface-emitting injection laser.

Kees A. Schouhamer Immink, president, Turing Machines Inc., Rotterdam, Netherlands. For pioneering and advancing the era of digital audio, video, and data recording.

Joseph (Yosi) Kost, professor, Department of Chemical Engineering, Ben Gurion University of the Negev, Beer-Sheva, Israel. For discoveries that led to ultrasonic drug release and self-regulated drug delivery systems.

Arnold Migus, directeur général, Centre National de la Recherche Scientifique, Paris, France. For contributions to ultrafast and ultra-high intensity lasers and their applications, especially to fast ignition for inertial confinement fusion.

Xi Yao, professor and dean, School of Electronic and Informatic Engineering, Jiaotong University, Xian, China. For contributions to science and engineering innovations for electroceramics.

NAE Newsmakers

Zdeněk P. Bažant, McCormick School Professor and Walter P. Murphy Professor of Civil and Environmental Engineering, Northwestern University, has been elected a **foreign member** of the **Accademia Nazionale dei Lincei** (the Italian National Academy), the oldest honorific scientific academy in the world. Dr. Bažant, only the second engineer to be elected a foreign member, will be inducted at a ceremony in June 2007.

Steven M. Bellovin, professor, Department of Computer Science, Columbia University, was presented with the **2007 National Information Systems Security Award** by the National Institute of Standards and Technology and the National Security Agency in a ceremony during the 22nd Annual Computer Security Applications Conference in Miami Beach, Florida, December 11–15, 2006. Recipients of the award are chosen for scientific or technological breakthroughs, outstanding leadership, highly distinguished authorship, or significant long-term contributions to the computer security field.

Anjan Bose, Regents Professor/ Distinguished Professor of Electric Power Engineering, Washington State University; **Herbert Gleiter**, professor, Research Center Karlsruhe, Institute of Nanotechnology, Germany; and **Kathleen C. Taylor**, retired director, Materials and Processes Laboratory, General Motors Corporation, were elected **foreign fellows** of the **Indian National Academy of Engineering**. Drs. Bose and Taylor attended the induction ceremony at the academy's annual meeting in December 2006 in Delhi.

Delbert E. Day, Curator's Professor Emeritus, Materials Science and Engineering, University of Missouri, received the **Distinguished Life Membership Award** from the American Ceramic Society at the organization's annual meeting in Cincinnati. This is the highest award bestowed by the American Ceramic Society.

Robert H. Dennard, fellow, IBM Thomas J. Watson Research Center, was awarded the **C&C Prize 2006** by the Foundation for C&C Promotion. Dr. Dennard was cited "for fostering today's IT industry prosperity by developing the fundamental structure of the one-transistor memory cell (DRAM) and by his contributions to the principles and practical applications of scaling of MOS transistor integrated circuits essential for computers and digital communication networks."

Two NAE members, **Joseph M. DeSimone**, W.R. Kenan Jr. Distinguished Professor of Chemistry and Chemical Engineering, University of North Carolina, and **Shirley Ann Jackson**, president, Rensselaer Polytechnic Institute, were elected **fellows** of the **American Association for the Advancement of Science**. Dr. DeSimone was honored for his contributions to polymer synthesis and processing, touching on everything from fundamental aspects of chemical systems to environmentally friendly ways of manufacturing polymers. Dr. Jackson was recognized for her efforts to advance science and scientific applications.

Charles Elachi, director, Jet Propulsion Laboratory, was honored as one of **"America's Best Leaders"** for 2006 by *U.S. News & World Report* and the Center for Public Leadership at the Harvard University John F. Kennedy School of Government. Dr. Elachi was one of 19 individuals recognized as leaders whose work has had a lasting impact.

Carl W. Hall, Engineering Information Services, Arlington, Virginia, received a **Distinguished Career Award** from the Department of Mechanical Engineering, University of Delaware, on April 28, 2006. Recipients are selected based on their "achievement, impact, uniqueness, and interest."

Jorg Imberger, director, Center for Water Research, University of Western Australia, has been made a **fellow** of the **American Geophysical Union**. The focus of Dr. Imberger's research is the effects on ecological systems of motion and mixing in lakes, estuaries, and coastal seas in response to natural forces and anthrogenic forcings.

Thomas Kailath, Hitachi America Professor of Engineering Emeritus, Department of Electrical Engineering, Stanford University, will be awarded the 2007 Institute of Electrical and Electronics Engineers (IEEE) **Medal of Honor** at the annual IEEE Honors Ceremony in June 2007. Professor Kailath will be honored for the "development of powerful algorithms in the fields of communications, computing, control and signal processing."

Norbert R. Morgenstern, University Professor of Civil Engineering Emeritus, University of Alberta, received the **Varnes Medal** from the International Consortium on Landslides. The Varnes Medal, awarded for internationally recognized leadership in the study of landslides, was presented to Dr. Morgenstern at UNESCO Headquarters in Paris.

Henry Petroski, Aleksandar S. Vesic Professor of Civil Engineering and professor of history, Duke University, received the **2006 Washington Award** from the Western Society of Engineers. Dr. Petroski was honored for promoting the public understanding of engineering theory and practice.

Gavriel Salvendy, Chair Professor and head, Industrial Engineering Department, Tsinghue University, Beijing, People's Republic of China, and professor, School of Industrial Engineering, Purdue University, received the **2006 Chinese Friendship Award**, the highest honor bestowed by the Chinese government on a foreign expert. The award was given in conjunction with the 57th anniversary of the founding of the People's Republic of China. Dr. Salvendy is the fourth person to receive an honorary doctorate in the 45-year history of the Chinese Academy of Sciences.

Frieder Seible, dean and Zable Professor and Reissner Professor, Irwin and Joan Jacobs School of Engineering, University of California, San Diego, received a **2006 Humboldt Research Award** from the Alexander von Humboldt Foundation. In fulfillment of the award, Dr. Seible will investigate

fundamental design concepts that could improve how structures perform under extreme loads caused by natural and manmade disasters. He will be hosted by the faculty of civil engineering at the Bauhaus University, Weimar. Dr. Seible will also visit and collaborate with other structural research institutes in Germany.

Richard L. Tomasetti, chairman, Thornton-Tomasetti, and adjunct professor, Columbia University, has been awarded the **2006 AIA New York Chapter Award** for outstanding contributions to architecture and engineering and for promoting collaboration in the greater design community.

NAE Member Gives Keynote Address at International Conference on Women in Science, Technology, and Engineering

Anne Stevens, chair and chief operating officer of Carpenter Technology Corporation, was the keynote speaker at the opening session of the International Conference on Women Leaders in Science, Technology and Engineering held January 8 to 10, 2007, in Kuwait. The goal of the conference, which was organized by the U.S. State Department, American Association for the Advancement of Science (AAAS), Arab Fund for Economics and Social Development, Kuwait Institute for Scientific Research, and Kuwait Foundation for the Advancement of Science, was to encourage a dialogue among women scientists and engineers in the region, and to encourage scientific and technical exchanges.

Left to right: Dr. Amel Al-Rashdan, associate research scientist, Central Analytical Laboratory, Kuwait Institute for Scientific Research; Dr. Sabah Al-Momin, research scientist, Biotechonology and Food Department, Kuwait Institute for Scientific Research; Marcia McNutt, president and CEO, Monterey Bay Aquarium Research Institute, and NAS member; and Anne Stevens.

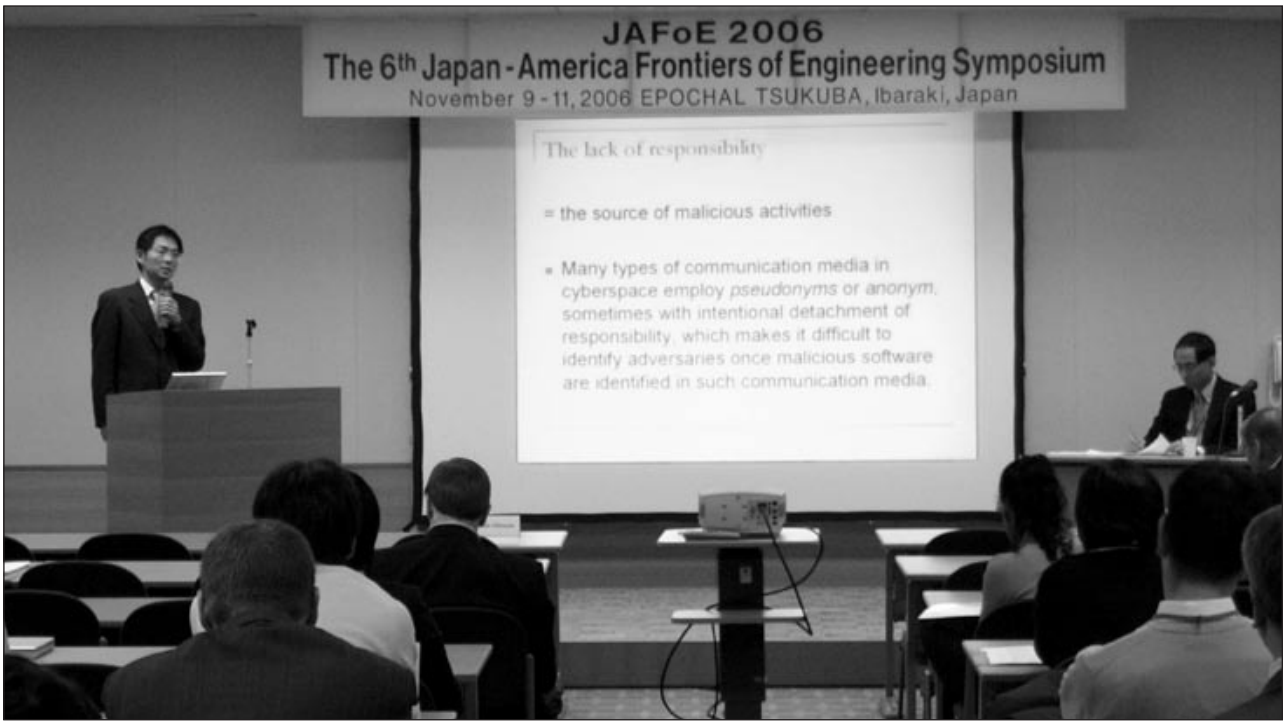
In Stevens' talk, "Global Trends," she described her experience in industry and discussed the importance of addressing human-capital issues in a global context. She also described her experiences as the representative for the National Academies on the Advisory Panel for the InterAcademy Council report, *Women for Science*, copies of which were distributed at the conference.

The highlight of the second day was a discussion led by Maryam Al-Thani, chair of the IEEE Women in Engineering Group, United Arab Emirates (UAE). Participants from Tunisia, Saudi Arabia, Kuwait, Egypt, and UAE found they had much in common and quickly established a sense of camaraderie.

More than 200 women scientists and engineers from 20 countries participated in the conference. The United States delegation included Stevens and NAS members Marye Anne Fox (chancellor, University of California, San Diego) and Shirley Malcom (AAAS).

A website is being created to facilitate communication among the participants and to encourage future collaboration. For more information about the conference or to receive a copy of *Women for Science*, please contact Catherine Didion, senior program officer, NAE, at *cdidion@nae.edu*.

2006 Japan-America Frontiers of Engineering Symposium



Youki Kadobayashi (left) of the Nara Institute of Science and Technology gives a presentation during the session on cybersecurity. U.S. session co-chair Cliff Wang of the U.S. Army Research Laboratory is on the right.

On November 9–11, 2006, the sixth Japan-America Frontiers of Engineering (JAFOE) Symposium was held at the Tsukuba International Congress Center in Tsukuba, Japan. Tsukuba, the home of Tsukuba Science City, a planned research and education community about 60 km northeast of Tokyo, is home to a large number of government and corporate R&D labs and two national universities. Approximately 60 engineers (30 from each country) and representatives of the Japan Science and Technology Corporation and Engineering Academy of Japan (NAE's partners in this program) attended the JAFOE Symposium.

The four sessions at the meeting were on cybersecurity, biomechatronics, systems and synthetic biology, and organic electronics. Presentations, by two Japanese and two Americans in each of the four areas, covered a wide range of topics, such as recent advances in self-directed network-intrusion detection, implantable microsystems for intracellular neural recording and stimulation, membrane protein chips, and flexible liquid-crystal displays with polymer walls and fibers.

The Thursday evening dinner speech was given by Dr. Yasunori Furukawa, CEO of Oxide Corporation, the first spin-off venture company from Japan's National Institute for Materials Science. Dr. Furukawa, a 47-year-old entrepreneur, described the growth of Oxide Corporation. Other highlights of the symposium included a poster session on the first afternoon during which participants described their technical work or research and break-out groups where participants had a chance to discuss public policy issues related to the presentations and develop "messages to society." The participants also toured the Japan Aerospace Exploration Agency's Tsukuba Space Center and the National Institute of Advanced Industrial Science and Technology's Science Square Tsukuba and Geological Museum. The tours were followed by a traditional Japanese dinner at a local restaurant.

Glenn H. Fredrickson, Mitsubishi Professor of Materials and Chemical Engineering and director of the Mitsubishi Chemical Center for Advanced Materials at the University of California, Santa Barbara, and Kazuhiro Sakurada, head, Nihon Schering Research Center, Nihon

On the second day of the symposium, participants met in small groups to develop "messages to society."

Schering K.K., co-chaired the organizing committee and the symposium. Dr. Fredrickson will continue as U.S. co-chair of the 2007 JAFOE symposium, which will be held November 5–7, 2007, at HP Laboratories in Palo Alto, California. The session topics for that meeting will be battery technologies, rocketry/aerospace, human-computer interaction, materials for medicine, and next-generation data centers.

Funding for the JAFOE Symposium was provided by the Japan Science and Technology Agency, the National Science Foundation, and the National Academy of Engineering Fund.

NAE has hosted annual U.S. Frontiers of Engineering meetings since 1995, and JAFOE meetings since 2000. NAE also has bilateral programs with Germany and India. FOE symposia, which bring together outstanding engineers aged 30 to 45 from industry, academia, and government, provide opportunities for leading young engineers to learn about cutting-edge developments, techniques, and approaches in many fields. Frontiers meetings also promote the establishment of contacts and collaboration among leaders of the next generation in engineering.

For more information about the symposium series or to nominate an outstanding engineer to participate in a future Frontiers meeting, contact Janet Hunziker at the NAE Program Office at (202) 334-1571 or by e-mail at *jhunziker@nae.edu*.

Report of the Foreign Secretary

George Bugliarello

I am happy to report that nine foreign associates have been elected for 2007 from nine different countries: Canada, France, Germany, Israel, Japan, People's Republic of China, Netherlands, Spain, and United Kingdom.

On November 8 to 11, the 2006 Japan-America Frontiers of Engineering (JAFOE) Symposium was held at the International Congress Center at Tsukuba, Japan. The symposium was sponsored by NAE, the Engineering Academy of Japan, and the Japan Science and Technology Agency and was organized by a committee co-chaired by a Japanese and U.S. engineer. NAE President **Wm. A. Wulf** welcomed the meeting participants on behalf of NAE; **Lance Davis**, NAE executive officer, was present, as was Janet Hunziker, program officer in charge of the FOE Program. The meeting was focused on four topics: cybersecurity, biomechatronics, synthetic biology, and organic electronics (see pp. 43–44 for more detail). The next international FOE meeting, the German-American FOE Symposium (GAFOE), will be held in April 2007 in Hamburg, Germany.

Before the JAFOE meeting, at the beginning of November, I met in Seoul, South Korea, with leaders of the National Academy of Engineering of Korea (NAEK), a member of the International Council of Academies of Engineering and Technological Sciences (CAETS), to discuss issues of common interest. At the invitation of NAE foreign associate **Dr. KunMo Chung**, president of Myongji University and of the Korean Academy of Science and Technology (KAST), I gave a lecture on urban sustainability at KAST.

Dr. Chung subsequently visited NAE in Washington to discuss the possibility of a meeting to review the feasibility of a thorium fuel cycle for nuclear reactors. Thorium is an abundant resource in several countries and does not have proliferation implications. The purpose of revisiting this controversial issue would be to review the current situation.

The day before the JAFOE Symposium, there was an NAE regional meeting and a tour of the Nippon Telegraph and Telephone Corporation Atsugi R&D Center, north of Tokyo. At the meeting, President Wulf presented an overview of current NAE programs and issues and encouraged a dialogue on common concerns among NAE members and guests. The night before the meeting, President Wulf, Lance Davis, Janet Hunziker, and I attended a dinner hosted by NAE foreign associate **Tatsuo Izawa**.

The next meeting of the joint Russian-American Academies Committee on Counterterrorism Challenges for Russia and the United States will be held in Moscow and St. Petersburg from March 19 to 28, 2007. The focus of the meeting will be on bioterrorism, transportation, and the vulnerabilities of energy infrastructure. An NAE-Chinese Academy of Engineering joint meeting is also being planned in the next few months to address questions of urban vulnerabilities to attacks with conventional explosives. **Siegfried Hecker**, a member of the International Affairs Committee of the NAE Council, will be co-chair of both the Russian-American and NAE-Chinese meetings.

We have initiated a pilot program of NAE members serving as liaisons to other academies around the world. NAE members **Subra Suresh** and **Darsh Wasan** have agreed to liaise with the Indian National Academy of Engineering, and NAE member **Albert Westwood** will liaise with the Russian Academy of Sciences.

We are currently engaged in discussions about possible collaborations with the Indian National Academy of Engineering and the Leopoldina Academy and Acatech in Germany. In addition, we continue to be engaged with the Mexican Academy of Engineering and FUMEC, the Mexican Foundation for Engineering and Science. It is heartening that academies around the world share our strong interest in collaborative activities.

Respectfully submitted,

George Bugliarello
Foreign Secretary

Call for Awards Nominations

For more than four decades, NAE has awarded five prizes (Founders Award, Arthur M. Bueche Award, Charles Stark Draper Prize, Fritz J. and Dolores H. Russ Prize, and Bernard M. Gordon Prize) to honor individuals who have made significant contributions to human well-being through advances in technology and significant innovations in engineering education. We invite you to help us continue this tradition by nominating outstanding engineers for next year's awards.

NAE Awards

The **Founders Award** honors an NAE member or foreign associate whose professional, educational, or personal achievement and accomplishments exemplify the ideals and principles of NAE. The **Arthur M. Bueche Award** is given to an engineer who has been actively involved in determining U.S. science and technology policy, promoting U.S. technological development, and improving relations among industry, government, and academia. The Founders and Bueche Awards are presented each fall at the NAE Annual Meeting. Each recipient receives a gold medallion, a hand-lettered certificate, and a $2,500 cash prize.

The **Charles Stark Draper Prize** is awarded annually for innovation and reduction to practice of an advancement in engineering or technology that contributes to the welfare and freedom of humanity. The biennial **Fritz J. and Dolores H. Russ Prize** is given in recognition of an engineering achievement that has contributed to the improvement of the human condition. Currently focused on bioengineering, the Russ Prize encourages collaborations between engineers and the medical and biological disciplines. The **Bernard M. Gordon Prize for Innovation in Engineering and Technology Education** is given annually to honor educators whose innovative programs have contributed to the quality of the engineering workforce. The focus is on innovations in curricular design, teaching methods, and technology-enabled learning, and the prize is shared equally between the recipient(s) and the institution. The Draper, Russ, and Gordon prizes, which include $500,000 cash awards, gold medallions, and hand-lettered certificates, are presented during National Engineers Week at the NAE Annual Awards Dinner. Nominators of the winning recipients are also invited to attend.

To Submit a Nomination

Nominations for the 2007 Founders and Bueche Awards and the 2008 Draper and Gordon Prizes will be accepted through **April 6, 2007**. A list of previous recipients can be found on our website (*www.nae.edu/awards*). Members and foreign associates have received nomination materials by mail. Nonmembers may obtain these materials from the NAE Awards Office at (202) 334-1628 or *awards@nae.edu* or may download them from our website.

Nomination forms should be mailed or faxed to: NAE Awards, National Academy of Engineering, 500 Fifth Street, N.W. (#1010), Washington, DC 20001, Fax: (202) 334-2290.

Christine Mirzayan Science and Technology Policy Fellows

Tylisha Baber

Tylisha Baber became a Christine Mirzayan Science and Technology Policy Fellow on January 8, 2006. She earned a B.S. in chemical engineering from North Carolina State University and a Ph.D. in chemical engineering from Michigan State University, where her dissertation was on the design and implementation of a biomass conversion process for improving the fuel properties of biodiesel. Tylisha is working on three projects at the NAE Center for the Advancement of Scholarship on Engineering Education (CASEE): characterizing the applications of educational virtual games to engineering; conducting an extensive review of the literature on determining the value of industrial experience for undergraduate and graduate students; and researching methodologies of evaluating the teaching of scholarship in engineering education.

Tiffani Bailey

Tiffani Bailey completed her Ph.D. in chemistry from North Carolina State University in December 2006. Her interdisciplinary research in chemistry and chemical engineering was focused on modifying chemical and physical properties at the liquid/solid interface to optimize surface chemistry applications. Tiffani earned her B.S. in chemistry from Hampton University.

At NAE, Tiffani is investigating ways to increase the engineering-education research capacity at historically black colleges and universities and Hispanic-serving institutions. She is also summarizing advances in engineering-education research and preparing policy and practice summaries on advancing scholarship in engineering education.

Simil Roupe

Simil Roupe is currently finishing her Ph.D. in biomedical engineering at Johns Hopkins University. Her thesis, which reflects her interest in how the brain learns and processes language, is focused on neural and vocal plasticity as a result of deafness in primates. In addition to a B.S.E in mechanical engineering, Simil received a B.A. in Spanish from Oral Roberts University in Tulsa. Before attending college, Simil worked for three years in an elementary school pursuing another interest of hers, improving science and mathematics education, especially for underrepresented groups.

While working with the NAE Committee on Diversity in the Engineering Workforce, she hopes to gain a broad perspective on how scientists can promote socially responsible public policy. In her free time, Simil likes to hike and play games with friends. She is looking forward to meeting people and making new friends during her time in Washington.

Carolyn Williams

Carolyn Williams is currently completing her Ph.D. in chemical engineering at the University of California, Los Angeles. Her dissertation research is focused on using synthetic-gene circuits in *Escherichia coli* to improve precursor and cofactor availability during secondary metabolite production. This research could create a dynamic microbial strain for the industrial-level synthesis of biopharmaceuticals and other desirable products. Carolyn completed her B.S. in biomedical engineering at Johns Hopkins University in 2003.

At NAE, she is involved in a new project, funded by NAE member **Steve Bechtel Jr.**, to study efforts around the country to incorporate engineering concepts into K–12 curricula. During her fellowship, she hopes to gain insight into the development of science and engineering curricula and the formulation of education policy. Carolyn enjoys reading, singing, snowboarding, and theater.

Engineer Girl! Website Hosts Outreach to Girl Scouts

The NAE website, *Engineer Girl!*, was developed as a resource to interest middle-school girls in learning more about engineering. The number one listing on *Google* for girls and engineering, *Engineer Girl!* (*www.engineergirl.org*) provides career guidance for students and parents, as well as links, games, and interesting facts about the history of women in engineering. The site has thousands of visitors per week.

This winter *Engineer Girl!* was an integral part of the "Introduce a Girl to Engineering" project in collaboration with the Girl Scout Council of America and National Engineers Week, which ran February 18 to 24, 2007. *Engineer Girl!* provided an online forum where Girl Scouts could ask women engineers from around the world questions about their work and their lives and receive feedback directly from them. Photographs and short personal histories of the women engineers were posted on the website.

The goal of the project was to encourage girls to explore the many opportunities and options offered by careers in engineering. To encourage their interest, the Girl Scout Council offered participating scout troops $50 grants to support activities that increase engineering awareness.

Suggestions and questions about the project should be directed to *engineergirl@nae.edu*.

NAE to Honor President Wm. A. Wulf with Philanthropic Initiative

Maxine Savitz

As we near the end of Dr. Bill Wulf's tenure as president of NAE, I would like to highlight a few of his many achievements. He assumed leadership of the organization at a time of intense turmoil, and to his enormous credit, he has restored the stability of the organization, rekindled the interest and confidence of the members in NAE's mission, and reestablished NAE's reputation in the National Academies and on the national scene.

Much has been accomplished under Bill's leadership. NAE now awards the Draper and Gordon Prizes yearly and the Russ Prize in alternate years—each worth $500,000. A new media relations program, the Public Understanding of Engineering Program, a robust multi-country Frontiers of Engineering Program for young engineers, a Diversity Program, and the Technological Literacy Program have brought engineering and NAE greater public recognition. The recently awarded experimental $1,000,000 Grainger Challenge Prize for Sustainability has added to NAE's visibility.

Bill has been a dynamic spokesperson for the importance of technology in our quality of life, national and homeland security, and globally sustainable development. He has been a tireless advocate of the U.S. engineering research enterprise as essential to the nation's economic well-being. Bill has strengthened the members' role in governance of NAE and NAE's role in the governance of the National Research Council. Farther from home, he has intensified NAE's participation in international activities and has traveled hundreds of thousands of miles each year to promote international understanding and cooperation.

Bill's most distinguished accomplishment has been to address problems in engineering education. Under his leadership, NAE has assumed a prominent role in efforts to ensure that U.S. engineers will be prepared to compete and lead in the emerging global economy. To maintain its position in the increasingly competitive global marketplace, the United States must have the best educated engineering workforce in the world. The Engineer of 2020 project, initiated under Bill's leadership, has determined that, in addition to strong technical skills, future U.S. engineers must have superb teamwork and communication skills, an understanding of ethical challenges that can arise with new technologies, a sensitivity to other cultures, and a commitment to lifelong learning. These engineers must be able to operate effectively in both business and academic settings.

It is my pleasure to announce that

last May the NAE Council decided to honor Bill's contributions by undertaking the Wm. A. Wulf Campaign for Engineering Excellence. The money raised in Bill's honor will provide seed funding for projects and programs that support NAE's tradition of excellence in engineering. In addition, the Center for the Advancement of Scholarship on Engineering Education will be renamed the Wm. A. Wulf Center for the Advancement of Scholarship on Engineering Education.

In the following pages you will see the names of NAE supporters, including members, spouses of deceased members, friends, corporations, and foundations. All of them made generous financial contributions to NAE in 2006; most of them are long-time supporters of our organization. We wish to express our deep and sincere appreciation of their support. Simply put, NAE could not exist without them.

I thank everyone who contributed in 2006 and request that you all join me in supporting the Wm. A. Wulf Campaign for Engineering Excellence in 2007. To date, about $4.5 million has been raised, and we hope the momentum continues.

As NAE vice president, I very much appreciate the generosity of NAE members and friends. Your support makes it possible for NAE to be proactive in anticipation of critical engineering issues. I feel confident that we will continue to grow the resources NAE needs to advise the nation and provide leadership to the engineering community. On behalf of the NAE officers, councillors, and staff, thank you.

Sincerely,
Maxine L. Savitz
NAE Vice President

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Calendar of Meetings and Events

March 13	NRC Governing Board Executive Committee Meeting
March 15	NAE Regional Meeting Georgia Institute of Technology Atlanta, Georgia
April 5	NAE Regional Meeting Stanford University Palo Alto, California
April 10	NRC Governing Board Executive Committee Meeting
April 11	Presidents' Committee Meeting
April 12	NAE Regional Meeting Carnegie Mellon University Pittsburgh, Pennsylvania
April 19	NAE Regional Meeting Northwestern University Evanston, Illinois
April 23	NAE Regional Meeting Purdue University West Lafayette, Indiana
April 26–28	German-American Frontiers of Engineering Symposium Hamburg, Germany
May 7–8	Convocation of Professional Engineering Societies
May 8	NRC Governing Board Executive Committee Meeting
May 8–9	NRC Governing Board Meeting
May 10–11	NAE Council Meeting Darby, Montana
June 6	NAE/NAEF Finance and Budget Committee Meeting
June 14	NRC Governing Board Executive Committee Meeting
June 20	NAE/NAEF Audit Committee Meeting

All meetings are held in the Academies buildings, Washington, D.C., unless otherwise noted. For information about regional meetings, please contact Sonja Atkinson at *satkinso@nae.edu* or (202) 334-3677.

In Memoriam

ALFRED J. EGGERS JR., 84, retired chairman and CEO, RANN Inc., died on September 22, 2006. Dr. Eggers was elected to NAE in 1972 for contributions to experimental and theoretical research in supersonic and hypersonic aerodynamics and in aerospace vehicle technology.

BEN C. GERWICK JR., 87, Honorary Chairman and senior technical consultant, Ben C. Gerwick Inc., died on December 25, 2006. Professor Gerwick was elected to NAE in 1973 for contributions and leadership in the application of engineering technology to underground, harbor, and ocean construction.

GEORGE HERRMANN, 85, Professor of Applied Mechanics, Emeritus, Stanford University, died on January 8, 2007. Dr. Herrmann was elected to NAE in 1981 for major contributions to the administration, publication, research, and teaching of applied and structural mechanics and his encouragement and mentoring of students and younger colleagues.

RALPH A. LOGAN, 80, Retired Distinguished Member of the Technical Staff, AT&T Bell Laboratories, died on December 1, 2006. Dr. Logan was elected to NAE in 1992 for contributions to the development of solid-state lasers.

A. RICHARD NEWTON, 55, dean of engineering, University of California, Berkeley, died on January 2, 2007. Dr. Newton was elected to NAE in 2004 for innovations and leadership in electronic design automation and for leadership in engineering education.

NICHOLAS ROTT, 88, retired professor of fluid dynamics, Swiss Federal Institute of Technology, and Retired Visiting Professor, Stanford University, died on August 10, 2006. Dr. Rott was elected to NAE in 1993 for teaching and research leading to fundamental advances in aerodynamics, acoustics, and fluid mechanics.

GEORGE A. SAMARA, 70, senior scientist, Sandia National Laboratories, died on December 30, 2006. Dr. Samara was elected to NAE in 1986 for contributions to the understanding of dielectric, ferroelectric, and ferromagnetic materials applications.

MILTON C. SHAW, 91, Professor of Engineering, Emeritus, Mechanical and Aerospace Engineering Department, Arizona State University, died on September 7, 2006. Professor Shaw was elected to NAE in 1968 for contributions to chemical synthesis, lubrication and bearing design, and machine tool design and performance.

ALAN F. SHUGART, 76, president, Al Shugart International, died on December 12, 2006. Mr. Shugart was elected to NAE in 1997 for contributions to disc memory devices and interfaces for personal computers.

JOHN W. SIMPSON, 92, retired executive vice president, Westinghouse Electric Corporation, and retired president, Westinghouse Power Systems Company, died on January 4, 2007. Mr. Simpson was elected to NAE in 1966 for his contributions to the field of nuclear power.

Publications of Interest

The following reports have been published recently by the National Academy of Engineering or the National Research Council. Unless otherwise noted, all 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 are subject to change without notice. Online orders receive a 10 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.*)

Frontiers of Engineering: Reports on Leading-Edge Engineering from the 2006 Symposium. This proceedings from the 2006 U.S. Frontiers of Engineering Symposium includes the 15 papers that were presented at the symposium, as well as the dinner speech by **W. Dale Compton**, Lillian M. Gilbreth Distinguished Professor of Industrial Engineering Emeritus, Purdue University, and NAE home secretary. The papers cover intelligent software systems and machines, the nano/bio interface, engineering for personal mobility, and supply chain management and applications with economic and public impact.

NAE member **Julia M. Phillips**, director, Physical, Chemical, and Nano Sciences Center, Sandia National Laboratories, chaired the organizing committee. Paper, $42.25.

Polar Icebreakers in a Changing World: An Assessment of U.S. Needs. The United States' long-standing national and strategic interests in the polar regions include citizens who live above the Arctic Circle and three year-round scientific stations in the Antarctic. Polar icebreaking ships are necessary to ensure access to both regions. For several decades, the U.S. government has supported a fleet of four icebreakers—three multi-mission U.S. Coast Guard (USCG) ships (*Polar Sea*, *Polar Star*, and *Healy*) and a National Science Foundation ship (*Palmer*), which is dedicated solely to scientific research. Although *Polar Star* and *Polar Sea* are at the end of their service lives, no funds have been allocated or plans made to extend the program, thus putting U.S. icebreaking capability at risk. This report concludes that the United States should continue to support its interests in the Arctic and Antarctic and maintain its leadership in polar science. The report makes several recommendations: (1) the United States should immediately program, budget, design, and construct two new polar icebreakers to be operated by USCG; (2) *Polar Sea* should remain mission capable, and *Polar Star* should remain available for reactivation until the new polar icebreakers enter service; (3) the USCG operations and maintenance budget should support an increased, regular, and influential presence in the Arctic, with support from other agencies; and (4) a Presidential Decision Directive should be issued to coordinate responsibilities and budgetary authority among the relevant agencies.

NAE member **Anita K. Jones**, Lawrence R. Quarles Professor of Engineering and Applied Science, University of Virginia, chaired the study committee. Paper, $30.50.

A Matter of Size: Triennial Review of the National Nanotechnology Initiative. The National Nanotechnology Initiative (NNI) was created in 2000 to focus and coordinate nanoscience and nanotechnology research and development (R&D) funded by several federal agencies and to ensure that research leads to the responsible development and deployment of nanotechnology for the economic benefit and security of the nation. In the 21st Century Nanotechnology Research and Development Act (P.L. 108-153), Congress directed the National Research Council to review the program every three years to monitor its overall progress. This report provides the results of the first review, which addresses the economic impact of nanotechnology developments and provides a benchmark for comparing U.S. R&D efforts to efforts by foreign competitors. In addition, the report provides an assessment of the current status of responsible development and a discussion of the feasibility of molecular self-assembly.

NAE members **James C. Williams**, Honda Professor of Materials, Ohio State University, chaired the study committee, and **Cherry A. Murray**, deputy director for science and technology, Lawrence

Livermore National Laboratory, was cochair. Other NAE members on the study committee were **Paul A. Fleury**, dean, Faculty of Engineering, Yale University, and **Mary L. Good**, Donaghey University Professor and dean, Donaghey College of Information Science and Systems Engineering (DCISSE), University of Arkansas at Little Rock. Paper, $41.50.

Third Report of the NAE/NRC Committee on New Orleans Regional Hurricane Protection Projects. This review of a June 1, 2006, draft study by the federal Interagency Performance Evaluation Task Force (IPET), which was established in 2005 to evaluate the performance of the New Orleans regional hurricane protection system during Hurricane Katrina, is the third report in a series by a joint National Academy of Engineering/National Research Council committee. Although the study under review includes more than 6,000 pages of text, figures, and tables, the committee finds that it has several shortcomings. First, IPET has not provided an executive summary that clearly explains the study objectives and findings. Because such a summary will be essential for policy makers and New Orleans officials and citizens, IPET should provide an easily understood summary that includes clearly stated conclusions linked to analyses in the body of the study. Second, despite advances in geotechnical evaluations at the sites of specific levee breaches, IPET's descriptions and analyses of geologic and soil conditions across the region are inadequate. In addition, estimates of storm surges and flooding must include characterizations of uncertainties.

NAE member **G. Wayne Clough**, president, Georgia Institute of Technology, chaired the study committee. Other NAE members on the committee were **Rafael L. Bras**, Edward A. Abdun-Nur Professor, Massachusetts Institute of Technology; **John T. Christian**, consulting engineer, Waban, Massachusetts; **Delon Hampton**, chairman of the board, Delon Hampton & Associates; and **Thomas D. O'Rourke**, Thomas R. Briggs Professor of Engineering, Cornell University. Free PDF available online at: *http://www.nap.edu*.

New Source Review for Stationary Sources of Air Pollution. The Clean Air Act established two programs—known collectively as New Source Review (NSR)—to regulate air pollution from large stationary sources, such as factories and electricity-generating facilities. NSR rules required that permits be issued for (1) building new facilities that could produce emissions above a specified level and (2) making changes to existing facilities that could increase emissions. In 2002, the Environmental Protection Agency (EPA) changed the NSR rules to clarify the modifications that require permits. In October 2003, EPA made additional, extremely controversial, changes, referred to as the equipment-replacement provision, that allow equipment replacement without an NSR permit as long as a facility does not exceed its maximum level of allowable emissions. In response to a request from Congress, EPA asked the National Research Council to estimate the effects of both sets of changes on human health, operating efficiency, pollution prevention, and pollution control. The report concludes that because of a lack of data and the limitations of current models, the effects of the NSR rule changes cannot be quantified with reasonable certainty. The report describes the data necessary to assess the impact of NSR rules and recommends that EPA and other government agencies undertake and sustain efforts to collect them. Although this report focuses specifically on the 2002 and 2003 rule changes, its analytic framework could also be applied to changes in other regulatory contexts.

NAE member **John C. Crittenden**, Richard Snell Presidential Chair of Civil and Environmental Engineering, Arizona State University, was a member of the study committee. Paper, $65.00.

Revealing the Hidden Nature of Space and Time: Charting the Course for Elementary Particle Physics. As part of Physics2010, the National Research Council was asked by the U.S. Department of Energy and the National Science Foundation to recommend priorities for the U.S. particle physics program for the next 15 years. Given the global nature of the field and the lack of a long-term and distinguishing strategic focus, the challenge for the study committee was to identify a compelling leadership role for the United States in elementary particle physics. This report provides an assessment of scientific challenges in particle physics, including key questions and experimental opportunities; a review of the current status and strategic framework of the U.S. program; and strategic principles and recommendations for sustaining a competitive, globally relevant U.S. particle physics program.

NAE members **Norman R. Augustine**, retired chairman and CEO, Lockheed Martin Corporation, and **Charles V. Shank**, E.O. Lawrence Berkeley National Laboratory, were members of the study committee. Paper, $36.00.

Countering Urban Terrorism in Russia and the United States: Proceedings of a Workshop. In early 2005, the National Academies Committee on Counterterrorism Challenges for Russia and the United States and the Russian Academy of Sciences Standing Committee on Counterterrorism held a workshop in Washington, D.C., on urban terrorism. Prior to the workshop, three working groups had been convened to investigate the vulnerabilities of energy systems and transportation systems and issues related to cyberterrorism. The working groups met with local experts and first responders, prepared reports, and presented their findings at the workshop. Other papers focused on integrated responses of various organizations to acts of urban terrorism, recent acts of terrorism, potential radiological, biological, and cyberterrorism, and the root causes of terrorism. These proceedings include the workshop presentations and reports by the working groups.

NAE member **Siegfried S. Hecker**, Visiting Professor, CISAC, Stanford University, chaired the study committee. Other NAE members on the study committee were **John F. Ahearne**, director, Ethics Program, Sigma Xi, The Scientific Research Society; **Lewis M. Branscomb**, Visiting Faculty, School of International Relations and Pacific Studies; **George Bugliarello**, President Emeritus and University Professor, Polytechnic University; **Anita K. Jones**, Lawrence R. Quarles Professor of Engineering and Applied Science, University of Virginia; and **Wm. A. Wulf**, president, National Academy of Engineering. Paper, $51.25.

Evaluation of the Sea Grant Program Review Process. The National Sea Grant College Program, created in 1966, has grown into a nationwide network of 30 individual Sea Grant programs located at some of the nation's top universities. Administered through the National Oceanic and Atmospheric Administration, this state-federal partnership funds marine and Great Lakes applied research, education, and outreach and has been a major source of funding for work on marine aquaculture; studies of shellfish diseases, aquatic nuisance species, coastal and estuarine ecology; seafood safety; and marine biotechnology, engineering, technology development, and policy. A 1994 National Research Council (NRC) report recommended that the Sea Grant Program develop a process for reviewing its individual programs on a four-year cycle; a review process was implemented in 1998 and modified by Congress in the 2002 reauthorization of the program. The legislation also included a request for this NRC study to assess the review process in terms of fairness and consistency and measures of improved performance. The report recommends improvements in the independent reviews conducted every four years and strategic planning for individual programs, more interaction between the National Sea Grant Office and individual programs, and annual assessments by the national office to improve the rating and ranking process.

NAE member **James M. Coleman**, Boyd Professor, Coastal Studies Institute, Louisiana State University and Agricultural and Mechanical College, was a member of the study committee. Paper, $43.25.

Hearing Loss Research at NIOSH: Reviews of Research Programs of the National Institute for Occupational Safety and Health. This is the first in a series of 15 reviews by the Institute of Medicine of research programs of the National Institute for Occupational Safety and Health (NIOSH). Taking into account important factors that are beyond the program's control, the committee finds that in the past decade (the period covered by this review), the Hearing Loss Research Program has made meaningful contributions to improving worker health and safety. However, the committee also finds that some of the research is narrowly targeted on areas less relevant to protecting workers. To help the program fulfill its stated mission of providing national and world leadership in reducing occupational hearing loss through a focused program of research and prevention, the committee recommends that program planning and implementation be improved; more program evaluations be implemented; additional intramural and extramural expertise be obtained, especially in epidemiology and noise-control engineering; and efforts be initiated to obtain surveillance data for occupational hearing loss and workplace noise exposure.

NAE member **William W. Lang**, president, Noise Control Foundation, was a member of the study committee. Paper, $45.75.

Renewing U.S. Telecommunications Research. The U.S. telecommunications infrastructure—made possible by research over the last several decades—is an essential element of

the U.S. economy. However, U.S. leadership in telecommunications technology is at risk because of a recent decline in domestic support for long-term, fundamental research. To help address this challenge, the National Science Foundation asked the National Research Council to assess the state of telecommunications research in the United States and recommend ways to halt the decline. This report provides an analysis of support levels, focus, and time horizons for telecommunications research by industry, an assessment of telecommunications research at universities, and a discussion of the implications of these findings for the health of the telecommunications sector. The report also provides recommendations for improving the situation and providing more funding for fundamental telecommunications research.

NAE member **Robert W. Lucky**, retired corporate vice president, research, Telcordia Technologies Inc., chaired the study committee. Other NAE members on the study committee were **John M. Cioffi**, Hitachi America Endowed Chair Professor of Electrical Engineering, Stanford University; **David G. Messerschmitt**, Roger A. Strauch Emeritus Professor of Electrical Engineering and Computer Sciences, University of California, Berkeley; **Lawrence R. Rabiner**, Professor II, Rutgers, The State University of New Jersey; **William J. Spencer**, Chairman Emeritus, SEMATECH; and **Jack Keil Wolf**, Stephen O. Rice Professor, University of California, San Diego. Paper, $18.00.

Surface Temperature Reconstructions for the Last 2,000 Years. This study was undertaken in response to a request from Congress for an assessment of efforts to reconstruct surface-temperature records for the Earth for the last 2,000 years and the implications of these efforts for our understanding of global climate change. Because widespread, reliable temperature records are only available for the last 150 years or so, scientists must estimate temperatures for the more distant past by analyzing "proxy evidence," such as tree rings, corals, ocean and lake sediments, cave deposits, ice cores, boreholes, and glaciers. Since the late 1990s, scientists have used sophisticated methods to combine proxy evidence from many locations to estimate changes in surface temperature in the last few hundred to few thousand years. This report concludes that scientists can now say, with a high level of confidence, that global mean surface temperature was higher in the last few decades of the 20th century than during any comparable period in the preceding four centuries. Large-scale reconstructions of surface temperatures for A.D. 900 to 1600 are less certain, although proxy evidence indicates that temperatures at many, but not all, individual locations were higher during the past 25 years than during any period of comparable length since A.D. 900. Statements about the hemispheric mean or global mean surface temperature prior to about A.D. 900 are less reliable, primarily because of the scarcity of precisely dated proxy evidence.

NAE member **Robert E. Dickinson**, professor, School of Earth and Atmospheric Sciences, Georgia Institute of Technology, was a member of the study committee. Paper, $40.00.

Drinking Water Distribution Systems: Assessing and Reducing Risks. Water distribution systems—pipes, pumps, valves, storage tanks, reservoirs, meters, fittings, and other hydraulic appurtenances—which deliver drinking water from centralized treatment plants or wells to consumers, cover almost one million miles in the United States and represent the major components of the physical infrastructure for water supplies. Thus, they constitute the primary management challenge for distributors, both in terms of operations and public health. Recent data on outbreaks of waterborne diseases suggest that distribution systems are sources of contamination that have yet to be addressed. This report evaluates recent data and approaches to risk characterization and identifies strategies for reducing risks posed by water-quality deteriorating events, such as backflow via cross connections and contamination during construction and repair activities, maintenance of storage facilities, and premise plumbing. The report also identifies advances in detection, monitoring, and modeling; analytical methods; and research and development opportunities that could help the water-supply industry reduce risks.

NAE member **Vernon L. Snoeyink**, Professor of Environmental Engineering Emeritus, University of Illinois, chaired the study committee. Paper, $69.00.

A Review of United States Air Force and Department of Defense Aerospace Propulsion Needs. Future U.S. Air Force and other military aerospace systems will be based on rocket and air-breathing propulsion systems. However, current trends, such as rising fuel prices, rising costs for sustaining aircraft, a shrinking domestic launch capability, and uncertainties about the availability and quality of domestic

researchers in the future, have intensified concerns about the development of these technologies and systems. To help assess the situation, the Air Force and U.S. Department of Defense asked the National Research Council to evaluate the U.S. aerospace propulsion-technology base to determine if current research is likely to support future war-fighting capabilities. This report provides an assessment of the existing technology base; an analysis of gaps in technology; and recommendations for supporting future capabilities that have not yet been fully defined under current plans for science and technology development. The report covers air-breathing technologies; rocket technologies for access-to-space and in-space operations and for missiles; and cross-cutting technologies.

NAE members on the study committee were **Donald W. Bahr**, retired manager, Combustion Technology, GE Aircraft Engines; **Yvonne C. Brill**, aerospace consultant, Skillman, New Jersey; **Dennis M. Bushnell**, chief scientist, NASA Langley Research Center; **David E. Crow**, retired senior vice president of engineering, Pratt and Whitney; **Thomas W. Eagar**, professor of materials engineering and engineering systems, Massachusetts Institute of Technology (MIT); **Gerard W. Elverum**, retired vice president and general manager, Applied Technology Division, TRW Space and Defense; **Edward M. Greitzer**, H.N. Slater Professor of Aeronautics and Astronautics, MIT; **Bernard L. Koff**, chief engineer, TurboVision; **Neil E. Paton**, chief technology officer, Liquidmetal Technologies; **Eli Reshotko**, Kent H. Smith Professor Emeritus of Engineering, Case Western Reserve University; **Kenneth M. Rosen**, president, General Aero-Science Consultants LLC; **Robert L. Sackheim**, assistant director and chief engineer for propulsion, NASA George C. Marshall Space Flight Center; and **Ben T. Zinn**, David S. Lewis Jr. Chair and Regents' Professor, Daniel Guggenheim School of Aerospace Engineering, Georgia Institute of Technology. Paper, $18.00.

Review of the Space Communications Program of NASA's Space Operations Mission Directorate. The Space Communications Office (SCO) of the National Aeronautics and Space Administration (NASA) has two primary roles: (1) to manage two of the communications networks that enable spaceflight operations and research; and (2) to integrate agency-wide telecommunications. In 2005, NASA asked the National Research Council to assess the overall quality of the space-communications program and the effectiveness of SCO. This report includes reviews of each element of the program—the space network, NASA's integrated space network, spectrum management, standards management, search and rescue, communications and navigation architecture, technology, and operations integration. The report reviews the plans for each program element, plan-development methodologies, linkages with the broader community, and overall capabilities and recommends improvements in SCO operations and organization.

NAE member **Antonio L. Elias**, executive vice president and general manager, Orbital Sciences Corporation, was a member of the study committee. Paper, $26.50.

Biological, Social, and Organizational Components of Success for Women in Academic Science and Engineering: Workshop Report. Although the number of women studying science and engineering (S&E) has increased dramatically (women now earn 51 percent of S&E bachelor's degrees and 37 percent of Ph.D.s, including 45 percent in biomedical fields), the number of women (especially African American women) who hold academic faculty positions is not commensurate with their share of the S&E talent pool. This discrepancy is apparent at the junior and senior faculty levels and at top research-intensive universities. Differences in career progression and success have been attributed to many factors: gender-based differences in cognitive abilities, career interests, and preferences; bias and discrimination; gender-based institutional policies and practices; and mistaken assumptions about gender roles. In December 2005, nationally recognized experts in a number of disciplines came together to address (1) the results of research on sexual differences in capability, behavior, career decisions, and achievement; (2) the role of organizational structures and institutional policies; (3) cross-cutting issues of race and ethnicity; (4) key research needs and experimental paradigms and tools; and (5) policy ramifications of research, particularly for evaluating current and potential academic faculty. This workshop report provides an introduction; summaries of panel discussions, including public comment sessions; and poster abstracts.

NAE members on the study committee were **Alice M. Agogino**, professor of mechanical engineering, University of California, Berkeley, and **Elaine Weyuker**, AT&T Fellow, AT&T Labs Research. Paper, $39.00

Testing of Defense Systems in an Evolutionary Acquisition Environment. The preferred process for the development of very complicated defense systems is evolutionary acquisition, whereby a system is developed in stages as part of a single acquisition program. By putting a high priority on the identification of failure modes early in system development, introducing only mature new technologies, and limiting the simultaneous introduction of new components or subsystems, the military hopes to reduce cost overruns, development delays, and system inadequacies. The recommendations in this report include: (1) modifying operational testing from pass/fail to continuous experimentation so that as much as possible can be learned about the strengths and weaknesses of system components; (2) focusing testing on detecting design inadequacies and failure modes; (3) modifying the incentive system in defense acquisition and testing to encourage learning and discovery; (4) coordinating the activities of system developers, government testers, and system users; (5) demonstrating the technological maturity of components prior to their use; and (6) taking advantage of information from prior stages of development to improve the test design of subsequent stages. In addition, the acquisition community needs more expertise in experimental design, statistical modeling, software engineering, and physics-based and operational-level modeling and simulation. Overall, the study committee recommends that the entire enterprise of operational testing be designed so that potential operational failure modes, limitations, and level of performance of a system can be identified early in the process.

NAE members **Seth Bonder**, Bonder Group, and **Stephen M. Pollock**, Herrick Emeritus Professor of Manufacturing, University of Michigan, were members of the study committee. Paper, $18.00.

Network Science. Although the U.S. Army depends on a wide range of interacting physical, informational, cognitive, and social networks, the fundamental understanding of how these networks work is still primitive. As the Army "transforms" to a force capable of network-centric operations (NCO), this gap must be closed. To help address this problem, the Army asked the National Research Council to determine if funding for research on network science could help close the gap. The study finds that, although networks are indispensable to the defense of the United States, no science today can supply the fundamental knowledge necessary for designing large, complex networks in a predictable way. The study also finds that current federal funding for network research is focused on specific applications rather than on the advancement of fundamental knowledge. This report argues for the importance of network science and explains how support for fundamental research on networks could help the Army advance its transformation to NCO.

NAE member **Charles B. Duke**, retired vice president and senior research fellow, Xerox Corporation, chaired the study committee. NAE member **John E. Hopcroft**, professor, Computer Science Department, Cornell University, was vice chair. Paper, $35.00.

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