Summer 2014

SHALE GAS: PROMISES AND CHALLENGES

The BRIDGE

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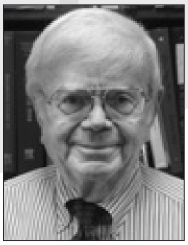
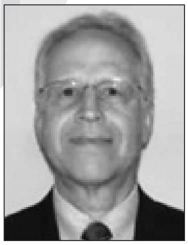
Editors' Note



John C. Angus



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NAE Topical Meeting: "Shale Gas: Promises and Challenges"

The recent revolution in methods for extracting natural gas and liquid hydrocarbons from shale formations presents the nation with unprecedented opportunities and challenges. Policy decisions concerning a host of technical, economic, and environmental questions will have to be made. To enhance public understanding of the issues related to shale gas development, Cleveland members of the NAE and others from local universities and groups organized a Topical Meeting, "Shale Gas: Promises and Challenges," covering

- impacts on the economy,
- science and technology challenges,
- energy security and independence, and
- environmental, health, and safety implications.

The meeting, held in Cleveland June 18–19, 2013, was hosted by Case Western Reserve University and cosponsored by Kent State and Cleveland State Universities. There were 25 speakers and over 900 attendees from business, academia, local, state, and regional government, and the public. Financial support was provided by 28 individuals, local foundations, and corporations. The organizing committee and staff were

Hunter Peckham (NAE), general chair
Steven Percy, cochair
Trevor Jones (NAE), development chair
John Angus (NAE)
Arthur Heuer (NAE)
Karen Mulloy
Vikas Prakash
Gary Previts
Beverly Saylor
David Zeng
Tom Barnish
Regina Loiko, conference administrator
Sharon Floyd, staff writer

The papers in this issue, drawn from the talks presented at the meeting, provide insight into some of the major issues surrounding shale gas development.

It should be recognized that the field is rapidly evolving and the level of understanding of these issues is changing. Interested readers are encouraged to explore the literature sources referenced in this issue; of particular note are reviews by Kell (2011), King (2012), King and King (2013), Vidic et al. (2013), and Zoback and Arent (2014). Useful information is also available from interest groups such as Resources for the Future (Krupnick et al. 2013, 2014) and the Environmental Defense Fund as well as government sources such as the Energy Information Agency, US Geological Survey, Department of Energy, and Environmental Protection Agency.

Background: Shale Gas, Horizontal Drilling, and Hydraulic Fracturing

Natural gas is found in conventional gas reservoirs, in coal beds, and in "tight gas" formations such as shale (Figure 1[1]). Shale gas may represent 32 percent of global and 27 percent of US natural gas resources (EIA 2013). However, until relatively recently it was not possible to economically recover this gas because of the extremely low permeability of shale. The use of hydraulic fracturing to increase the permeability, together with horizontal drilling, has enabled the development of this resource.

To access shale gas a well is first drilled vertically then directed in a relatively horizontal direction to follow the

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[1] *Managing Editor's note*: Color images are printed in this issue thanks to a special contribution from the editors and their colleagues involved in the Cleveland NAE Topical Meeting on which this issue is based.

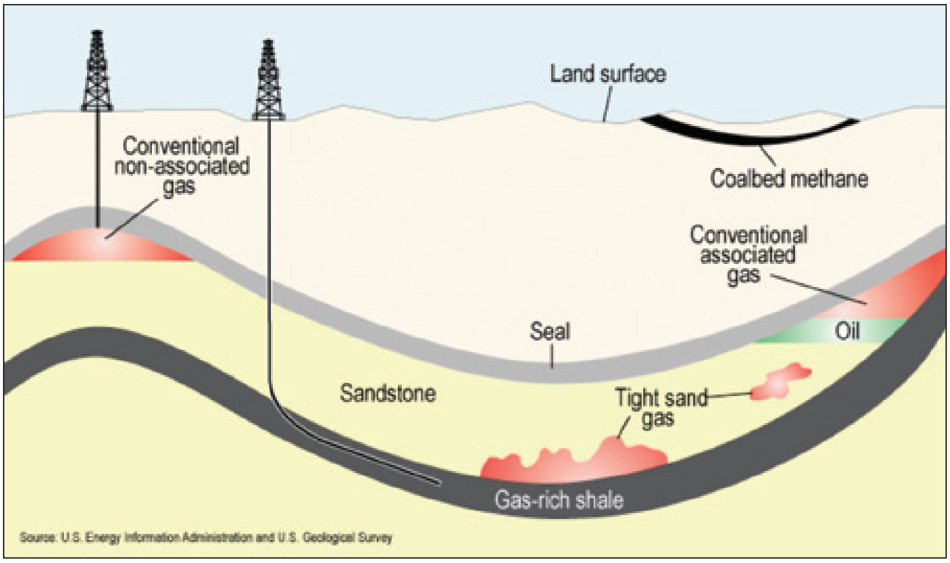

FIGURE 1 The geology of natural gas resources. Schematic diagram showing the several types of natural gas deposits (not to scale). The horizontal section of a shale gas well, along which the fracturing takes place, can extend 2 kilometers or more. A seal is a low-permeability layer of rock that limits upward flow of fluids. Source: US Energy Information Agency and US Geological Survey, February 2011.

shale formation. Depending on the local conditions the vertical portion of the well is typically several kilometers deep, and the horizontal section two kilometers or more in length. The vertical and horizontal sections of the well are cased with steel and cement during drilling.

To liberate the natural gas, the casing of the horizontal section is perforated with a series of explosive charges along its length. Fractures in the shale caused by these explosions are expanded and extended using water under high pressure (the *hydraulic* fracturing). The water used for hydraulic fracturing contains a proppant, typically sand, which keeps the fractures *propped* open after the pressure is reduced. Small concentrations of additives for surface tension and viscosity control, corrosion inhibition, and biocides for suppression of biological growth are used as well.

Over time, after the pressure is reduced, this water flows back out of the well. In addition to this flowback water, additional water is produced during the lifetime of the well.

An excellent overview of horizontal drilling and hydraulic fracturing was provided by Zoback and Arent (2014) in the previous issue of the *Bridge*.

Some Perspective

The application of horizontal drilling and hydraulic fracturing is bringing about a sea change in the nation's energy posture. Figure 2 shows the dramatic projected increase in US production of natural gas from shale. Natural gas is the largest single component of the country's total energy *production*: in 2012 it accounted for 31 percent of the total energy produced in the United States (EIA 2014). However, petroleum and other liquid fuels remain the largest

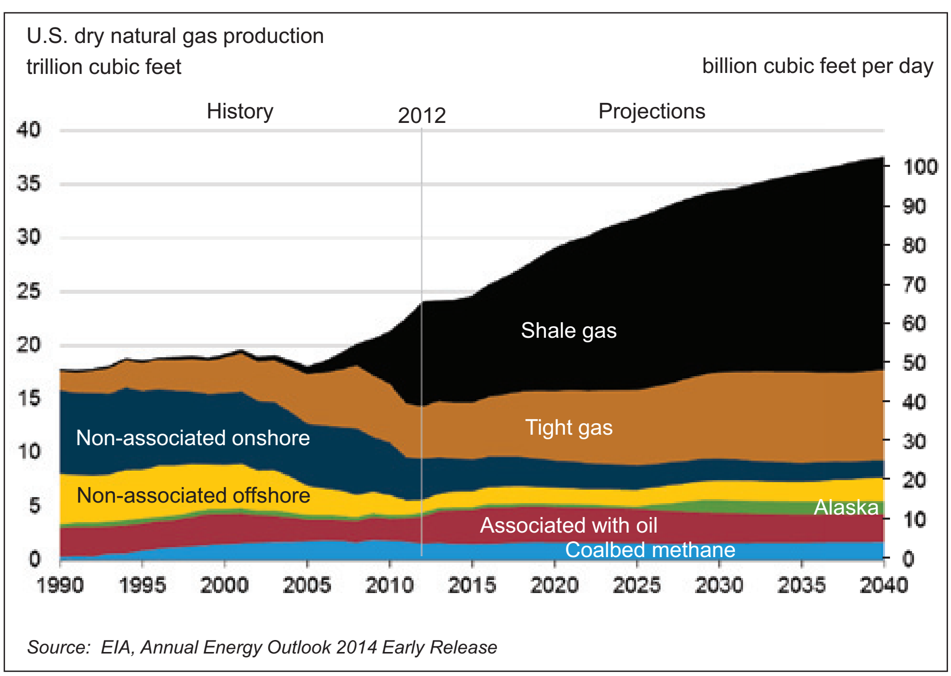

FIGURE 2 Current and projected sources of natural gas production in the United States. Source: EIA (2014).

component in US energy *consumption*; in 2012 they accounted for 37 percent compared to 27 percent for natural gas (EIA 2014).

The changes brought about by production of shale gas are likely to have a significant impact on the global energy picture, as discussed in this issue by Finley and Rühl (2014), as well as a positive influence on the competitiveness of US industry. Swift (2014) in this issue describes how these changes will particularly affect the US chemical industry, which relies on natural gas not only as fuel but also as a primary feedstock for the production of basic chemicals. Furthermore, shale gas is projected to appreciably reduce US net energy imports (Figure 3). Recent events in Eastern Europe are likely to enhance the strategic importance of alternative supplies of natural gas.

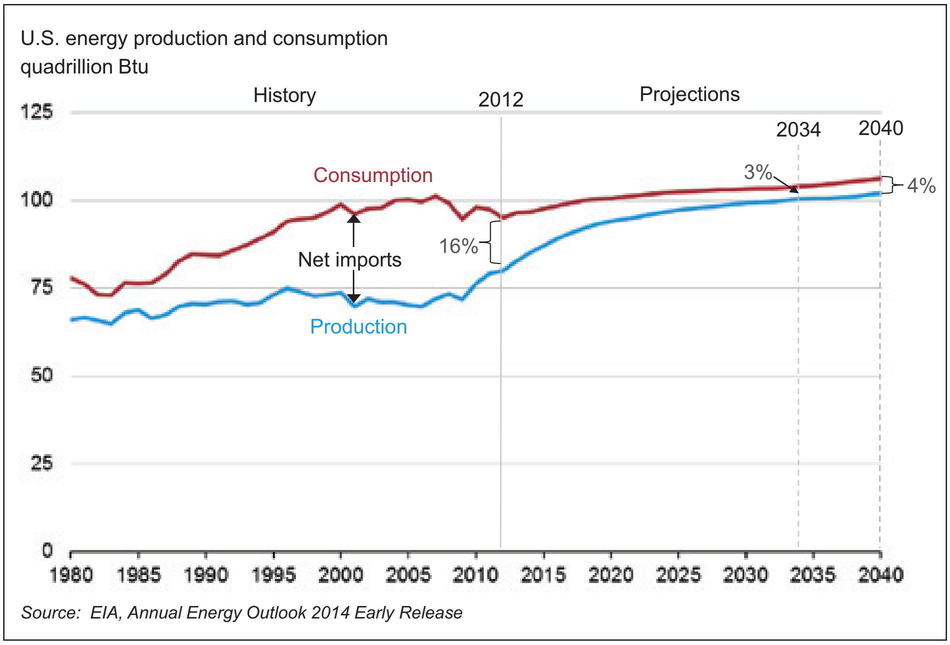

FIGURE 3 Net actual and projected energy imports for the United States. Source: EIA (2014).

Unresolved Issues

Public Concerns

Several major points became clear from the presentations and the public response to the meeting. There is a very strong public desire for unbiased information on the potential benefits and downsides of natural gas development. Many fear that the individuals and communities most impacted by development will not share appropriately in the benefits, a point made in this issue by Lendel (2014). Air quality and worker health and safety are other significant concerns; they are discussed in this issue by Pétron (2014) and Mulloy (2014), respectively.

Water Resources

The impact of shale gas development on water resources is perhaps the most serious concern expressed by the general public. Hydraulic fracturing in *vertical* wells has been used in the oil and gas industry for decades. However, the recent major expansion of hydraulic fracturing to *horizontal* wells has increased both the demand for water and the potential impact on water resources. Careful handling of the large volumes of water generated from well operations is required. Contamination can occur from surface operations—for example, through a breach of containment ponds, operator error, equipment failure, truck accidents, and illegal dumping. All of these risks can be reduced through the use of best management practices and appropriate regulations.

A related public concern is the lack of complete disclosure in all cases of the chemicals added to the water used in hydraulic fracturing. The migration, decomposition, and fate of these additives are areas of active research.

Reclamation and recycling of the water from well operations can significantly reduce both the demand for groundwater resources and the amount of water that must be disposed of in injection wells, thus diminishing the potential for induced seismicity. The technology and tradeoffs of water recovery are reviewed in this issue by Silva and colleagues (2014).

A separate problem is the potential contamination of groundwater by methane. Dramatic examples of methane contamination of well water have been cited, but careful studies to understand the source and magnitude of this problem are still ongoing. In this issue Bachu and Valencia (2014) discuss the potential for methane contamination by loss of well integrity. The available data indicate that surface operations involving handling and storage of wastewater are a more likely source of contamination than underground activities. With a few exceptions (e.g., Heisig and Scott 2013), baseline data on hydrocarbon contamination *before* oil and gas operations take place are often not available. This highly contentious issue of groundwater contamination by methane is being played out in a series of articles in the *Proceedings of the National Academy of Sciences* and elsewhere (e.g., Davies 2011; Fontenot et al. 2013; Jackson et al. 2011, 2012, 2013; Li and Carlson 2014; Molofsky et al. 2013; Olmstead et al. 2013; Osborn et al. 2011a, 2011b; Saba and Orzechowski 2011; Schon 2011; Vidic et al. 2013; Warner et al. 2012, 2013).

A major report from the Environmental Protection Agency on the potential impacts of hydraulic fracturing on drinking water resources is in preparation. A progress report has been released (EPA 2012) and a draft report for public comment and peer review is expected this year (EPA 2014).

Air Quality and Carbon Balance

Replacement of coal by methane for power generation and other uses will result in an overall reduction in particulates, sulfur dioxide, nitrogen oxides, and mercury. Furthermore, if losses during production and distribution are sufficiently low, replacement of coal by natural gas will help the overall atmospheric carbon balance, partially mitigating the potential for global warming.

However, there is still uncertainty about the magnitude of fugitive gas emissions from the natural gas production and distribution system. One study (Howarth et al. 2011) suggested that up to 8 percent of the methane from shale gas production escapes to the atmosphere, offsetting any potential mitigation effect. In contrast, other studies (Burnham et al. 2012; Jiang et al. 2011; Laurenzi and Jersey 2013), using lower estimated emissions and a life cycle approach to account for all offsets, found an overall reduction of carbon emission through the use of natural gas. This debate continues. A recent major study indicated that current EPA estimates of methane leakage are low (Brandt et al. 2014). In this issue one of the coauthors of that study discusses various types of measurements of hydrocarbon emissions and the effect of emissions on air quality (Pétron 2014).

In Summary

Much more comprehensive data and analyses are needed to support sound engineering and policy decisions for natural gas development. Many competing near- and long-term interests must be balanced to avoid nonoptimal, short-term consumption of these major hydrocarbon deposits. With wise decisions this resource has the potential to provide a bridge to a renewable and sustainable energy future; unwise decisions can leave the global community with a continuing unsustainable reliance on fossil fuels.

References

Bachu S, Valencia RL. 2014. Well integrity and risk assessment. The Bridge 44(2):28–33.

Brandt AR, Heath GA, Kort EA, O'Sullivan F, Pétron G, Jordaan SM, Tans P, Wilcox J, Gopstein AM, Arent D, Wofsy S, Brown NJ, Bradley R, Stucky GD, Eardley D, Harriss R. 2014. Methane leaks from North American natural gas systems. Science 343:733–735.

Burnham A, Han J, Clark CE, Wang M, Dunn JB, Palou-Rivera I. 2012. Life-cycle greenhouse gas emissions of shale gas, natural gas, coal, and petroleum. Environmental Science and Technology 46:619−627.

Davies RJ. 2011. Methane contamination of drinking water caused by hydraulic fracturing remains unproven. Proceedings of the National Academy of Sciences 108:E871.

EIA [US Energy Information Administration]. 2013. Technically Recoverable Shale Oil and Shale Gas Resources: An Assessment of 137 Shale Formations in 41 Countries Outside the United States. Washington. Available at www.eia.gov/analysis/studies/worldshalegas/.

EIA. 2014. Annual Energy Outlook 2014: Early Release Overview. Washington. Available at www.eia.gov/forecasts/aeo/er/.

EPA [US Environmental Protection Agency]. 2012. Study of the potential impacts of hydraulic fracturing on drinking water resources: Progress report. Washington: US EPA Office of Research and Development, December. EPA/601/R-12/011; available at www2.epa.gov/hfstudy/study-potential-impacts-hydraulic-fracturing-drinking-water-resources-progress-report-0.

EPA. 2014. Study of the potential impact of hydraulic fracturing on drinking water resources. Draft report, publication pending. Washington.

Finley M, Rühl C. 2014. Trends in the world energy balance. The Bridge 44(2):9–14.

Fontenot BE, Hunt LR, Hildenbrand ZL, Carlton DD, Hyppolite O, Walton JL, Hopkins D, Osorio A, Bjorndal B, Oinhong HH, Schug KA. 2013. An evaluation of water quality in private drinking water wells near natural gas extraction sites in the Barnett shale formation. Environmental Science and Technology 47:10032–10040.

Heisig PM, Scott T-M. 2013. Occurrence of methane in groundwater of south-central New York State, 2012: Systematic evaluation of a glaciated region by hydrogeologic setting. Scientific Investigations Report 2013-5190. Washington: US Geological Survey.

Howarth RW, Santoro R, Ingraffea A. 2011. Methane and the greenhouse-gas footprint of natural gas from shale formations. Climatic Change 106:679–690.

Jackson RB, Osborn SG, Vengosh A, Warner NR. 2011. Reply to Davies: Hydraulic fracturing remains a possible mechanism for observed methane contamination of drinking water. Proceedings of the National Academy of Sciences 108:E872.

Jackson RB, Vengosh A, Darrah TH, Warner NR, Down A, Poreda RJ, Osborn SG, Zhao K, Karr JD. 2012. Increased stray gas abundance in a subset of drinking water wells near the Marcellus shale gas extraction. Proceedings of the National Academy of Sciences 110:11213–11214.

Jackson RE, Gorody AW, Mayer B, Roy JW, Ryan MC, Van Stempvoort DR. 2013. Ground water protection and unconventional gas extraction: The critical need for field-based hydrogeological research. Ground Water 51:488–510.

Jiang M, Griffin MW, Hendrickson C, Jaramillo P, VanBriesen J, Venkatesh A. 2011. Life cycle greenhouse gas emissions of Marcellus shale gas. Environmental Research Letters 6: article no. 034014.

Kell S. 2011. State oil and gas agency groundwater investigations and their role in advancing regulatory reforms. A two state review: Ohio and Texas. Presentation to Ground Water Protection Council, Oklahoma City, August.

King GE. 2012. Hydraulic fracturing 101: What every representative, environmentalist, regulator, reporter, investor, university researcher, neighbor, and engineer should know about estimating frac risk and improving frac performance in unconventional gas and oil wells. Society of Petroleum Engineers Report, SPE 152596.

King GE, King DE. 2013. Environmental risk arising from well construction failure: Difference between barrier and well failure, and estimates of failure frequency across common well types, locations and well age. Society of Petroleum Engineers Report, SPE 166142, Production and Operations 28:323–344.

Krupnick A, Gordon H, Olmstead S. 2013. Pathways to Dialogue: What the Experts Say about the Risks of Shale Gas Development. Washington: Resources for the Future.

Krupnick AJ, Kopp RJ, Hayes K, Roeshot S. 2014. The Natural Gas Revolution: Critical questions for a Sustainable Energy Future. Washington: Resources for the Future.

Laurenzi IJ, Jersey GR. 2013. Life cycle greenhouse gas emissions and freshwater consumption of Marcellus shale gas. Environmental Science and Technology 47:4896–4903.

Lendel I. 2014. Social impact of shale development on municipalities. The Bridge 44(2):47–51.

Li H, Carlson KH. 2014. Distribution and origin of groundwater methane in the Wattenberg oil and gas field of northern Colorado. Environmental Science and Technology 48:1484–1491.

Molofsky LJ, Connor JA, Wylie AS, Wagner T, Farhat SK. 2013. Evaluation of methane sources in groundwater in Northeastern Pennsylvania. Ground Water 51:333–349.

Mulloy KB. 2014. Occupational health and safety considerations in oil and gas extraction operations. The Bridge 44(2):41–46.

Olmstead SM, Muehlenbachs LA, Shih J-S, Chu Z, Krupnick AJ. 2013. Shale gas development impacts on surface water quality in Pennsylvania. Proceedings of the National Academy of Sciences 110:4962–4967.

Osborn SG, Vengosh A, Warner NR, Jackson RB. 2011a. Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. Proceedings of the National Academy of Sciences 108:8172–8176.

Osborn SG, Vengosh A, Warner NR, Jackson RB. 2011b. Reply to Saba and Orzechowski and Schon: Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. Proceedings of the National Academy of Sciences 108:E665–E666.

Pétron G. 2014. Air pollution issues associated with shale gas production. The Bridge 44(2):19–27.

Saba T, Orzechowski M. 2011. Lack of data to support a relationship between methane contamination of drinking water wells and hydraulic fracturing. Proceedings of the National Academy of Sciences 108:E663.

Schon SC. 2011. Hydraulic fracturing not responsible for methane migration. Proceedings of the National Academy of Sciences 108:E664.

Silva JM, Gettings RM, Kostedt WL, Watkins VH. 2014. Produced water from hydrofracturing: Challenges and opportunities for reuse and recovery. The Bridge 44(2):34–40.

Swift TK. 2014. Shale gas production: Effects on investment and competitiveness in the US chemical industry. The Bridge 44(2):15–18.

Vidic RD, Brantley SL, Vandenbossche JM, Yoxtheimer D, Abad JD. 2013. Impact of shale gas development on regional water quality. Science 340(6134), doi:10.1126/science.1235009.

Warner NR, Jackson RB, Darrah TH, Osborn SG, Down A, Zhao KG, White A, Vengosh A. 2012. Geochemical evidence for possible natural migration of Marcellus Formation brine to shallow aquifers in Pennsylvania. Proceedings of the National Academy of Sciences 109:11961–11966.

Warner NR, Kresse TM, Hays PD, Down A, Karr JD, Jackson RB, Vengosh A. 2013. Geochemical and isotopic variations in shallow groundwater in areas of the Fayetteville Shale development, north-central Arkansas. Applied Geochemistry 35:207–220.

Zoback MD, Arent DJ. 2014. Shale gas development: Opportunities and challenges. The Bridge 44(1):16–23.

Increases in oil and gas production from hydraulic fracturing are greatly reducing US imports and rejuvenating the country's export business.

Trends in the World Energy Balance

Mark Finley and Christof Rühl

Mark Finley

Christof Rühl

The year 2012 produced a number of headlines in energy-related news. Some of the trends reported are part of long-term changes in the world energy landscape, others show adaptations to shorter-term disruptions.

The United States experienced a large increase in oil and gas supplies, while in China, Germany, and Japan—together representing a quarter of global GDP—renewables captured a greater share than nuclear power. Liquefied natural gas (LNG) trade, on the other hand, declined for the first time since coverage of gas trade began 30 years ago. And record amounts of coal, exiled from the United States by the shale gas revolution, were shipped to Europe.

Beyond those headlines, energy developments looked unsurprising. Consumption growth slowed to 1.8 percent, below its 10-year average, for all fuels (bar renewables and hydropower) and in all regions except Africa—quite in line with a lackluster global economic performance overall.

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This article draws on BP's 62nd annual *Statistical Review of World Energy*, published in June 2013. The *Statistical Review* has provided high-quality, objective, and globally consistent data on world energy markets since 1952. A widely respected and authoritative publication in the field of energy economics, it is used for reference by the media, academia, world governments, and energy companies. A new edition is published every June; the 63rd edition will be available June 16, 2014, at BP.com/statisticalreview.

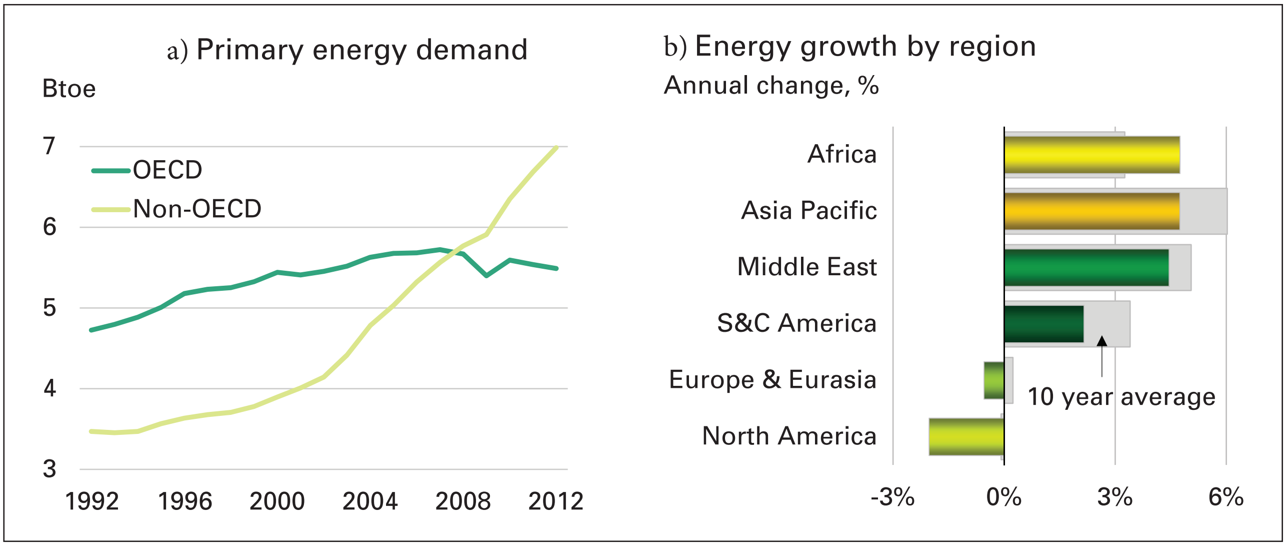


FIGURE 1 (a) Yearly world demand for primary energy, 1992–2012. Btoe = billions of tonnes of oil equivalent. (b) Changes in energy demand by region in 2012. S&C America = South and Central America. Source: 2013 *Statistical Review of World Energy*.

The headline figures looked relatively normal, but the energy system is good at adjusting to a changing world, and sometimes it drives change. This long-term context is the best starting point for assessing the data trail of a year in which energy markets appeared calm but actually involved lots of adjustments.

Long-Term Energy Trends

We start with the long-term trend of primary energy demand shown in Figure 1.[1] Principal among these trends is the ongoing shift of the world's economic center of gravity toward the so-called developing world, for our purposes the countries other than the 34 members of the Organization for Economic Cooperation and Development (OECD).

Changes in Consumption and Production

Since 1992 global energy consumption has increased by 52 percent, and during the past 10 years it increased by 30 percent, almost all of which was outside the OECD. In contrast, OECD consumption fell during 4 of the past 5 years—despite positive GDP growth in 3 of the 4 years. In 2012 OECD energy consumption declined by 1.2 percent, again despite positive GDP growth (1.4 percent), and hard on the heels of a similar result for 2011. In fact, it returned to where it was in 2002—although cumulative GDP growth was 26 percent over that same period.

There is a rarely noted corollary to this shift in the center of gravity: As the non-OECD economies industrialize, they also develop more resources. The data clearly reveal that the industrializing part of the world not only outpaced the OECD in terms of consumption growth but also contributed a fair share to energy production. In 2002–2012 the non-OECD countries accounted for 98 percent of global energy production growth. A breakdown of production growth by region during 2012 is shown in Figure 2a. Net growth in Asia outstripped that of the rest of the world, with regional growth led by China and other non-OECD producers.

Changes in global proved reserves[2] of oil and gas since 1982 are shown in Figure 2b. Proved reserves change not only with technology and discovery but with prices as well, and this was evident in the United States when gas prices fell and some reserves became unprofitable to produce. Whereas 2012 saw growth in proved oil reserves of 15 billion barrels, proved gas reserves recorded their first decline ever in the BP database (−0.5 trillion cubic meters, Tcm), driven by lower prices and reduced drilling activity in the United States.

[1] *Primary energy* refers to forms of energy before conversion to electricity or refined products.

[2] *Proved reserves* can with reasonable certainty be economically produced under current market and operating conditions; they differ from *technically recoverable reserves*.

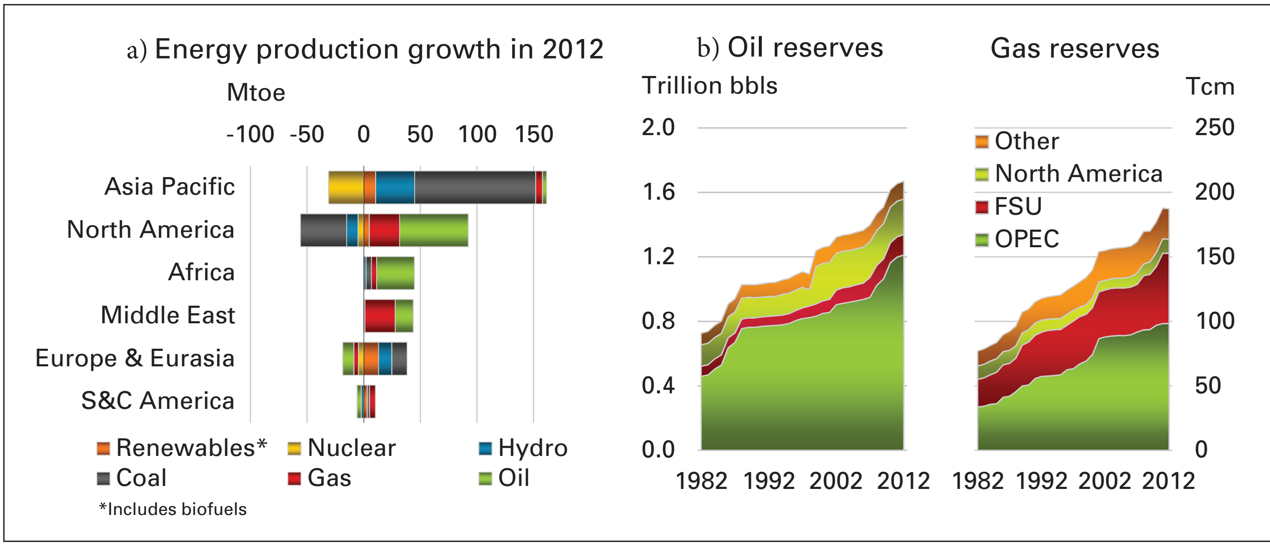


FIGURE 2 (a) Changes in energy production in 2012. Mtoe = millions of tonnes of oil equivalent; S&C America = South and Central America. (b) Proved oil and gas reserves, 1982–2012. bbls = barrels; FSU = former Soviet Union; TCM = trillions of cubic meters. Source: 2013 *Statistical Review of World Energy*.

Even with the decline in 2012, proved gas reserves were up 21 percent since 2002 and 59 percent compared to 1992. And proved oil reserves were 28 percent higher than in 2002 and 60 percent higher than in 1992—despite the production of nearly 600 billion barrels of oil during that period.

Energy Prices

Approximately 87 percent of world energy is provided by fossil fuels, and there has been an unprecedented rise in the prices of these fuels over the past decade (Figure 3). In inflation-adjusted terms, average annual oil prices (as indicated by the North Sea marker grade of crude "Brent") for the last five years were 230 percent higher than for the same period 10 years ago; for coal the increase was 140 percent; and for natural gas, 90 percent. Since 2008 the spread across fossil fuel prices has also widened, with oil prices significantly outstripping those of both natural gas and coal.

There was a moderation of sorts in 2012. Oil remained relatively stable, but at record levels; gas prices bifurcated across regions, dropping massively in the United States (−32 percent) but rising in all other regions of the world; and the price of coal declined everywhere.[3] We will look at the reasons as we go along.

Higher prices take their toll. They affect demand, particularly in countries where economic growth is less energy intensive and consumers are not sheltered by subsidies. Thus changing price differentials will shape the global fuel mix, and high prices will eventually trigger supply responses.

These effects were evident in 2012. Oil, the highest priced of all fossil fuels per unit of energy content, continued a slide in global market share that started with the first oil price shock in 1973; in 2012 it was the only fossil fuel that lost market share in OECD and non-OECD countries alike.

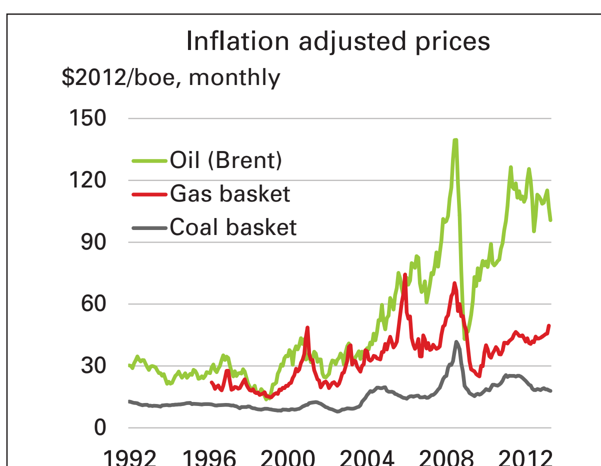


FIGURE 3 World energy prices, 1992–2012, in 2012 dollars per barrel of oil equivalent (boe). Sources: 2013 *Statistical Review of World Energy*; ICIS Heren Energy; Energy Intelligence Group; McCloskey; Platts.

[3] *Editors' note:* See "Shale Gas Production: Effects on Investment and Competitiveness in the US Chemical Industry," by T. Kevin Swift in this issue, for discussion of the effects of price differences between the United States and Europe.

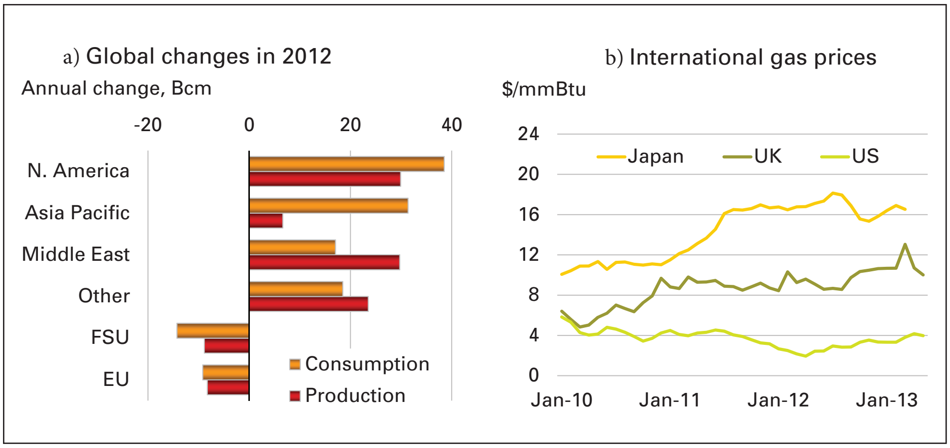


FIGURE 4 Global natural gas balance. (a) Global consumption and production changes in 2012. "Other" includes Africa, South and Central America, and portions of Europe/Eurasia not included in the European Union (EU) and former Soviet Union (FSU). Bcm = billions of cubic meters. (b) International gas prices. mmBtu = million British thermal units. Sources: 2013 *Statistical Review of World Energy*; ICIS Heren Energy; Energy Intelligence Group.

Price spreads between natural gas and coal triggered competition between them, often across borders, with inexpensive gas displacing coal in the United States and coal displacing expensive gas in Europe. Much of this effect has resulted from the large supplies of US gas made available by hydraulic fracturing.

Global Natural Gas Balance

Two trends dominated the evolution of natural gas markets in the past few years: the rapid growth of shale gas in the United States and the expansion of global LNG. Changes in the global production, consumption, and prices of natural gas are shown in Figure 4.

Production and Consumption

US production continued to grow in 2012, if at a slower pace: it rose by 4.7 percent (32.9 billion cubic meters, Bcm), significantly below the record expansion—7 percent, 44.9 Bcm—of 2011. The slowdown was driven by the reorientation of US drilling away from gas and toward higher-priced oil. The impact on gas output would have been much sharper without the rapid growth in the production of oil and liquid-rich gas.

Global production grew by 1.9 percent (72 Bcm), also below average. In addition to the slowdown in US production growth, the European Union (−5.5 percent, −8.3 Bcm) and former Soviet Union (−1.4 percent, −8.9 Bcm) registered the largest regional production declines. In contrast, LNG trade declined for the first time in the BP data series, even though LNG imports to Asia continued to rise, affected by Japan's post-Fukushima fuel shift.

Global gas consumption rose by 2.2 percent (82 Bcm) in 2012, faster than in 2011 but below the 10-year average (2.7 percent). The world's largest volume gain in consumption (31.6 Bcm, 4.1 percent) was in the United States—a larger increase than that of any other region.

These developments, together with the continuing impact of Japan's adjustment to the loss of nuclear power, shaped gas markets in 2012 and created an important example of interfuel competition.

Prices

Regional gas prices moved in lockstep with these patterns, as illustrated in Figure 4b. Spreads widened: US prices recorded their lowest annual average since 1999, Japanese import prices reached a new average annual record high, and UK spot prices edged up as global competition for LNG tightened the market in Europe. In the United States natural gas prices (as indicated at the Henry Hub distribution point in Louisiana) were on a declining path from late 2011 to April 2012, when they reached a low of $1.83/mmBTU.

As a result, many dry shale gas plays became uneconomic and producers reduced activity, as evidenced, for example, by a 46 percent decline in the overall gas rig count (Figure 5a). A switch from dry to wet[4] and associated gas production, encouraged by high oil prices, helped to contain the impact: nonassociated shale gas production grew by 84 Bcm in 2011, but by a mere 10 Bcm a year later, while associated gas output rose by 12 Bcm, accounting for 36 percent of total US production growth (Figure 5b). Declining supply growth continued into 2013.

Coal to Gas Switching

Unusually warm winter weather at the start of 2012 curtailed heating demand, but US gas production continued

[4] *Dry gas* is basically methane. *Wet gas* also contains other, higher-molecular-weight hydrocarbons, called *natural gas liquids*, which tend to have a higher value in an environment of high oil prices.

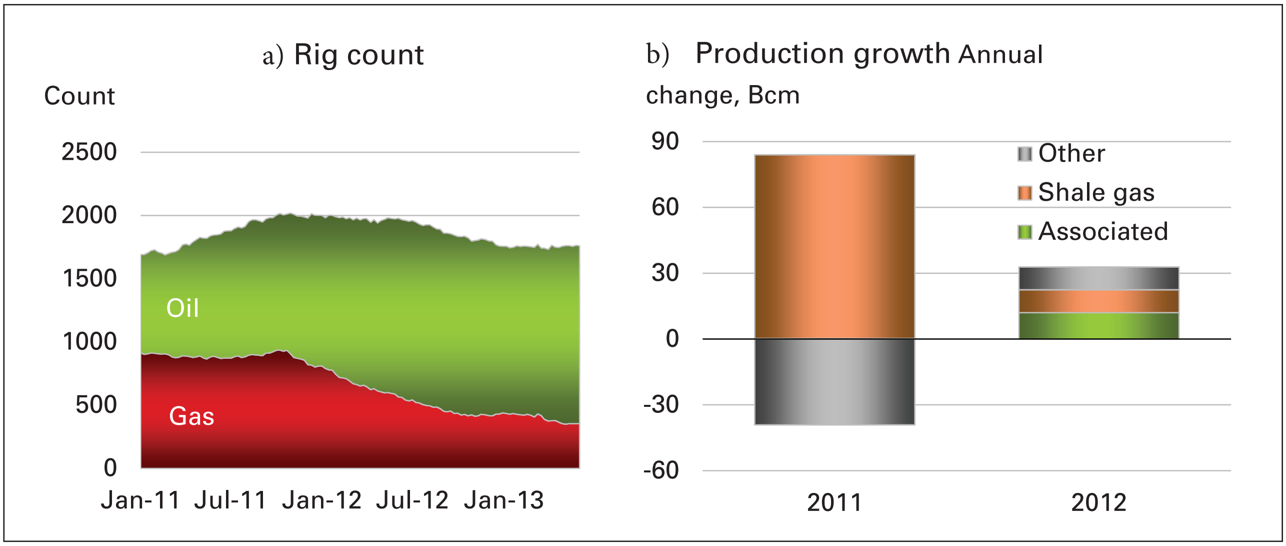


FIGURE 5 (a) US rig count. (b) US natural gas production changes. "Associated" = gas produced in association with oil production. "Other" = all other natural gas production excepting shale and "associated." Bcm = billions of cubic meters. Sources: 2013 *Statistical Review of World Energy*; Energy Information Administration (www.eia.gov); Baker Hughes (www.bakerhughes.com).

to expand, which left markets oversupplied and inventories high. Some relief was provided by lower pipeline imports from Canada (4.4 Bcm), higher exports to Mexico (3.4 Bcm), and falling net LNG imports (4.1 Bcm).

The main balancing factor, however, was the one sector flexible enough to absorb the surplus natural gas: the power sector, which required gas prices to fall far enough to compete with coal for baseload electric power generation. The dramatic shift from coal to natural gas for electric power production in the United States is shown in Figure 6. All told, an additional 44 Bcm of gas went into the power sector in 2012, boosting gas-fired power generation by 21 percent (217 terawatt hours, TWh)—the largest new increment of any fuel in US power generation in at least 40 years—and leading to an all-time high for gas-fired power generation (1,295 TWh). As a direct result, coal-fired power generation fell to its lowest level since 1987, and US coal consumption declined by almost 12 percent in 2012, the largest decline worldwide.

The switch reported here accentuates a trend in gas-fired generation expansion by an average of 6.5 percent per annum and coal-fired generation decline by 5.6 percent per annum since 2007.

Impacts of Tight Oil Production

The story of "tight oil" (oil bound tightly in shale and other formations and requiring unconventional means for extraction) has been well documented. The massive resource base in the United States and innovations in horizontal drilling and hydraulic fracturing have greatly enhanced production of tight oil. In 2012 the United States recorded the largest annual gain in oil production both in the world and in US history.

The extraction of tight oil was the driver of supply growth. US oil production has expanded by 2 million barrels per day (mmb/d) over the last five years, the largest increase in the world and twice that of Iraq (1 mmb/d), which accounted for the second largest increment. Output in 2012 in North Dakota and

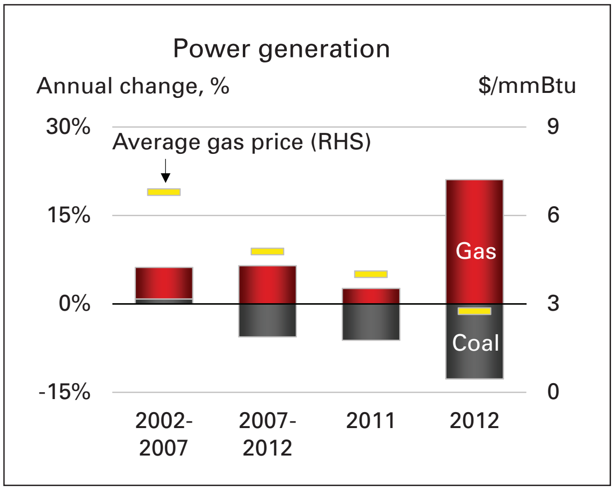


FIGURE 6 Coal to natural gas switching, 2002–2012. mmBtu = millions of British thermal units; RHS = right-hand scale. Sources: 2013 *Statistical Review of World Energy*; Energy Information Administration (www.eia.gov); Platts.

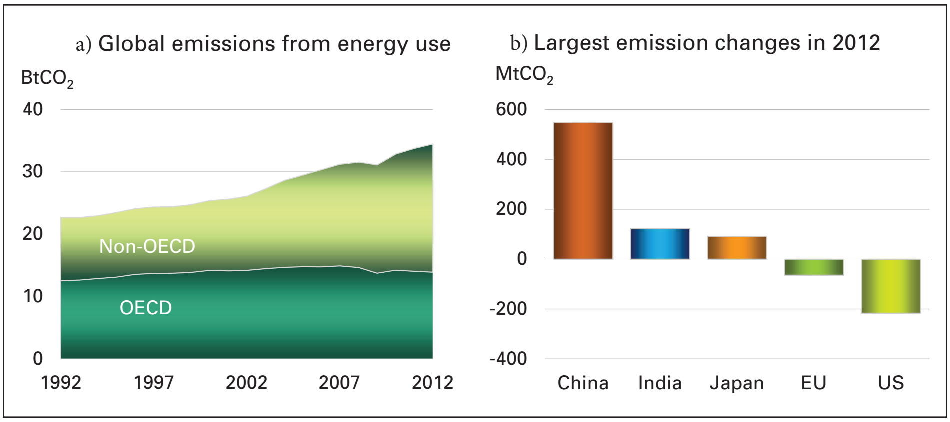


FIGURE 7 (a) Global carbon emissions from energy use, 1992–2012. Bt = billions of tonnes. (b) Carbon emission changes during 2012. Mt = millions of tonnes. Source: 2013 *Statistical Review of World Energy*.

Texas, the states with the most productive oil formations, rose by nearly 800,000 barrels per day.

The strong growth in US output, combined with lower consumption, has dramatically reduced overall US oil import requirements. Since peaking in 2005, US net imports have fallen by 4.5 mmb/d, or 36 percent—a reduction nearly as large as the entire 2012 consumption of the world's third largest consumer, Japan. (Over that same period, Chinese net oil imports rose by 2.8 mmb/d or 84 percent.) And although the United States and European Union imported similar amounts in 2005, in 2012 US net imports were nearly one-third below those of the European Union.

Changes in Carbon Emissions

Global carbon emissions from energy consumption are estimated to have risen by 1.9 percent (723 million tonnes [Mt] of CO_2) in 2012, slightly faster than primary energy consumption (1.8 percent). During the past decade, emissions grew 2.8 percent per annum, also faster than total energy consumption (2.6 percent); a slow decline in the OECD (−0.2 percent p.a.) was more than offset by growth in non-OECD countries (5.8 percent p.a.). Unsurprisingly, the largest growth in 2012 emissions associated with consumption came from China (548 Mt, 6 percent) and India (122 Mt, 6.9 percent); Japan also recorded a significant increase (92 Mt, 6.7 percent) as it adjusted to the loss of nuclear energy. These changes are shown in Figure 7.

The United States recorded the largest emission reductions worldwide, dropping faster than the European Union. This may seem unexpected, given the aggressive EU policy stance with regard to emission reduction. And considering just the emissions avoided through the growth of renewable power or, for that matter, reduced emissions from oil consumption, the European Union reduced more than the United States. But the effects of these measures were overwhelmed by the fuel switch in power generation discussed above—from gas to coal in the European Union and from coal to gas in the United States. In Europe, coal-fired power benefited from weak coal prices, in part due to coal displaced in the United States by cheaper shale gas, combined with relatively high regional natural gas prices.

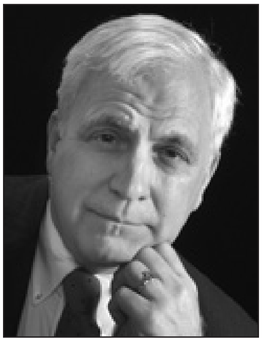
Summary

Energy concerns everyone. Starting with many moving parts and taking the long-term perspective, there are many examples of adjustments, some of them well attuned to long-established trends—for example, the continued relative growth of the emerging economies. Some of these changes may be temporary as supply, demand, and prices continue to change and consequently influence the competition between fuels.

However, there are several key "takeaways." First, in 2012 shale gas production in the United States enabled natural gas to "win" its competition with coal in the power generation sector, lowering overall energy costs and thus boosting the economy while at the same time moderating carbon emissions. Second, increases in tight oil production, again from hydraulic fracturing, are having a profound impact on the US oil supply picture, greatly reducing imports of petroleum and rejuvenating the country's export business in refined products. Third, policy matters, particularly market-oriented policies that encourage competition and innovation in accessing, producing, and consuming energy.

Shale gas production—the #1 development in the US chemical industry since the 1930s—has been a game changer for the US natural gas markets, with manifold effects.

Shale Gas Production
Effects on Investment and Competitiveness in the US Chemical Industry



T. Kevin Swift is chief economist and managing director of the American Chemistry Council.

T. Kevin Swift

This paper reports current and projected effects of dramatic increases in US shale gas production on new investment in—and hence the competitiveness of—the US chemical industry. Similar to the manufacturing industries, the chemical industry uses hydrocarbons, including natural gas, to provide much of the basic process energy for heating and steam. However, it also uses natural gas as a primary feedstock for many of its largest processes, and is therefore particularly sensitive to natural gas costs.

Energy and Feedstock Costs in the Chemical Industry

Processes in the chemical industry tend to be very energy intensive. Figure 1 shows the fraction of total costs that arise from energy, fuel, and feedstocks for various segments of the US chemical industry: two major inorganic chemicals, chlorine/caustic soda and sodium carbonate, are listed at the top, followed by petrochemicals, then plastics and resins, and two fertilizers at the bottom. Blue indicates the cost associated with fuel, power, and feedstocks; red shows other costs (e.g., other raw materials, labor, maintenance).

Note that even for inorganic chemicals, which do not use hydrocarbons as feedstocks, the energy cost is an appreciable fraction (26–41 percent) of total production costs; chlorine/caustic soda plants, for example, are very large consumers of electricity (for electrolysis). For most of the petrochemicals and resins, which do use hydrocarbons as a feedstock, the percentage of

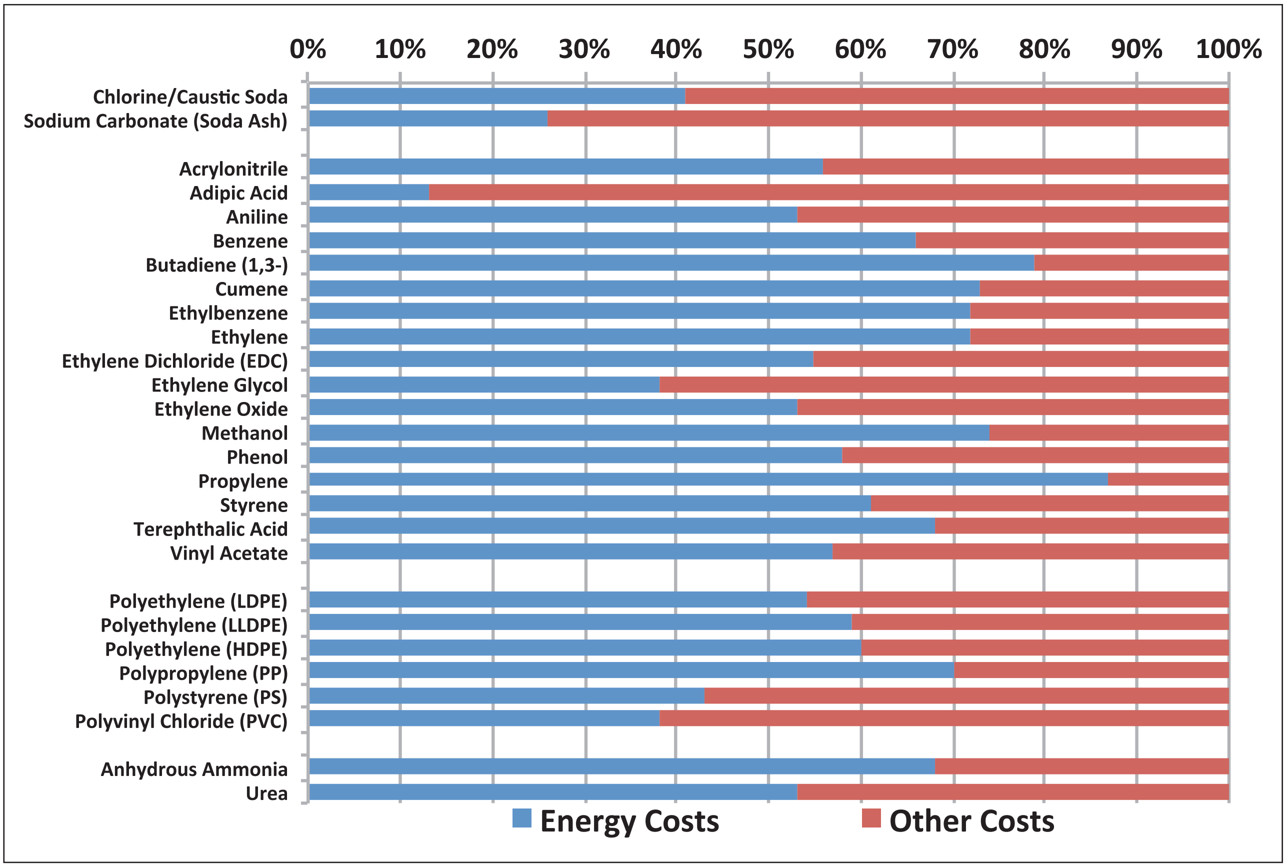


FIGURE 1 Fuel, power, and feedstock costs (blue) in various segments of the chemical industry as a percent of total costs. Red designates other costs such as raw materials, labor, and maintenance. Top grouping is inorganic chemicals, second is petrochemicals, third plastics and resins, and fertilizers are listed at the bottom. Reprinted with permission from Swift and Moore (2013).

total costs assignable to fuel, power, and feedstocks is well over 50 percent. Finally, energy and feedstock costs are the major cost components associated with the production of fertilizers such as anhydrous ammonia, which is made directly from natural gas.

In recent years energy prices in the United States have been falling both in absolute terms and relative to other countries. From 2005 to 2012 the price of natural gas in the United States fell by more than 50 percent, although the general trend of petroleum prices was upward. These changes are having significant positive effects on US competitiveness, as illustrated in the example of ethylene production.

Ethylene Production Costs

Naphtha, a hydrocarbon feedstock derived from oil refining, is used in Western Europe to produce ethylene and related products. Its cost is highly correlated with the cost of petroleum, which has increased. In the United States, on the other hand, ethane is a primary feedstock used for similar purposes. Largely derived from natural gas liquids, its cost is correlated with that of natural gas, which has decreased. Thus in Western Europe the costs of feedstock for ethylene production have risen while in the United States they have declined (Swift and Moore 2013). These changes have greatly enhanced the competitiveness of the US industry compared to that of Western Europe.

Global Ethylene Supply

Because ethylene is a major chemical intermediate for a host of downstream products around the globe, its cost can serve as a bellwether for the chemical industry.

Changes in the cost of producing ethylene are vividly illustrated in Figure 2, which shows the global ethylene supply curves for 2005 (blue) and 2012 (red). In 2005 the cost of producing ethylene in the United States was higher than in all other major markets. But by 2012 the production costs in Western Europe and Asia had gone up significantly, while US costs were markedly less than

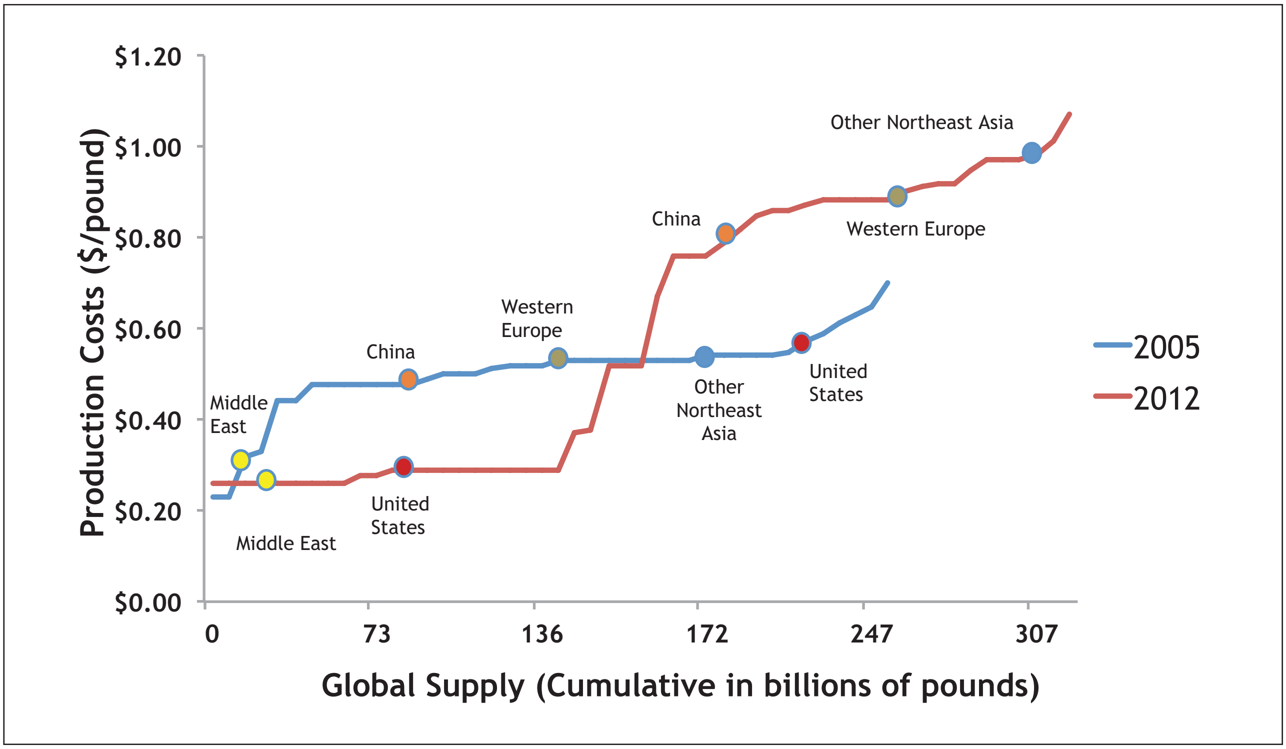


FIGURE 2 Global ethylene supply curves in 2005 and 2012. Petrochemical production costs shown by country and region. Middle East = Saudi Arabia; Other Northeast Asia = Japan and Korea. Reprinted with permission from Swift and Moore (2013).

those in Western Europe, China, and Northeast Asia (Japan and Korea) and only slightly higher than those in Saudi Arabia. However, by the end of this decade producers in Saudi Arabia will have to switch from natural gas feedstocks to more costly naphtha derived from petroleum (Swift and Moore 2013); unless Saudi Arabia subsidizes the cost of naphtha, that change will offset its current cost advantage. As a result, the United States will likely be in an even stronger relative position.

Announced Capital Projects

The American Chemistry Council (ACC) currently estimates that, thanks to the new shale gas development, by 2020 there will be over $100 billion (2012 dollars) in incremental new investment in the US chemical industry, over half of it from overseas (i.e., foreign direct investment). It is possible that over $110 billion (in 2012 dollars) will ultimately be invested.[1]

In association with these investments, about 150 chemical industry capital projects in the United States have recently been announced—about 50 percent in bulk petrochemicals, 25 percent in plastics and resins, and the remainder in fertilizer and inorganic chemicals. Approximately three quarters of these developments are planned for the Gulf Coast region and the rest in the Ohio Valley and other Midwest locations. The number and mix of projects will, of course, change with time, but the basic trend is clear: the number of announced capital projects in the US chemical industry almost doubled between January and June 2013.

In addition, the Ohio Valley and the rest of the Midwest will see significant increases in downstream industries, such as plastics and resins manufacturing. For example, in Hudson, Ohio, Little Tikes is expanding its production of plastic toys, and a number of other manufacturers (e.g., molders, fabricators) of finished plastic products are likewise expanding. The ACC has counted over 20 such initiatives since mid-2012, making Ohio the third largest state with these investments.

When completed, these capital projects are anticipated to add over $70 billion annually to total US chemical production. Furthermore, they will dramatically enhance job growth in the chemical and ancillary industries, US competitiveness, and hence exports of chemical products.

[1] The peak year for investment spending was predicted to be 2016, but this will likely slip.

Job Growth

Direct job growth in the chemical industry by the end of the decade is estimated at 46,000 jobs, which by itself is good but will not make a major impact on overall US employment. However, the chemical industry is a major purchaser of goods and services from associated industries that are much more labor intensive, and this activity is expected to add approximately 262,000 jobs. Moreover, indirect economic activity in other segments of the economy associated with shale gas investment is projected to add another 224,000 jobs, bringing the total job growth attributable to enhanced shale activity to over 500,000 jobs by 2020 (Swift and Moore 2013).

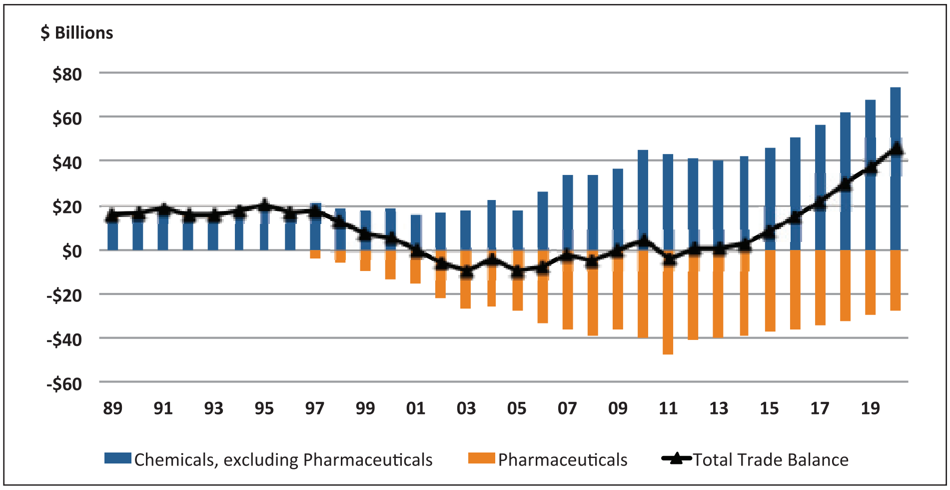


FIGURE 3 Past and projected balance of payments of the US chemical and pharmaceutical industries, 1989–2019. Sources: US Census Bureau report on *US International Trade in Goods and Services*, available at www.census.gov/foreign-trade/; Swift and Moore (2013).

US Competitiveness and Exports

The improved global competitiveness of the US chemical industry is leading to increased exports of chemical products. For example, the export of US-produced resins and plastics has virtually doubled in the past decade from about 10 to 20 percent of total output, and the American Chemistry Council expects that this share will grow to over 30 percent by 2020.

As a corollary of these trends, the US chemical industry may capture market share from Western Europe (Swift and Moore 2013; Swift et al. 2013). In fact, ACC analysis indicates that the trade surplus in chemicals will eventually outweigh the trade deficit for pharmaceuticals (Figure 3).

Concluding Thoughts

Shale gas production—the number one development in the US chemical industry since the 1930s—has been a game changer for the US natural gas markets, with manifold effects:

- It has improved the competitiveness of US manufacturing, especially chemicals.
- It is fostering a wave of new greenfield investment, over 50 percent of which is from foreign companies—the United States is now recognized as a very good place for chemical production.
- The new investment is generating new business, jobs, and tax revenues.
- With global integration and renewed competitiveness, US exports will capture greater global market share. The chemical industry is projected to become a major net positive contributor to the US balance of payments by 2020.

In summary, there is a very promising future for the US chemical industry.

References

Swift T, Moore M. 2013. Shale Gas, Competitiveness, and New US Chemical Industry Investment: An Analysis Based on Announced Projects. Washington: American Chemistry Council.

Swift T, Moore M, Sanchez E. 2013. Year-End 2013 Chemical Industry Situation and Outlook. Washington: American Chemistry Council.

For natural gas to provide a bridge to a greener future, industry leaders, regulators, researchers, and engineers need to work together using reliable data to effectively curb emissions.

Air Pollution Issues Associated with Shale Gas Production

Gabrielle Pétron

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The impacts of natural gas extraction on air quality have not been accorded the level of attention that potential water contamination has received, but they are equally consequential to deliberations on shale gas production. The benefits to US (and eventually global) society of exploiting unconventional sources of natural gas have been well explored. But although natural gas burns cleaner than coal, the full climate impact of its use depends on accurate data on the emissions of air pollutants associated with gas extraction. Environmental impact assessments that are required before extensive development rely on models based on emission inventories to predict how the activity will affect regional air quality, and regulators in turn rely on such information both for overseeing current emissions and for predicting impacts of future energy development. Emission inventories are also used to support US commitments to provide emission estimates of greenhouse gases to the United Nations Framework Convention on Climate Change.

This article provides technical background, reviews trends in atmospheric pollutants, and describes air- and ground-based measurement methods to investigate emissions from oil and gas production operations and their

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Any opinions, findings, conclusions, or recommendations expressed in this article are those of the author and do not necessarily reflect the views of the US National Oceanic and Atmospheric Administration or the University of Colorado Boulder.

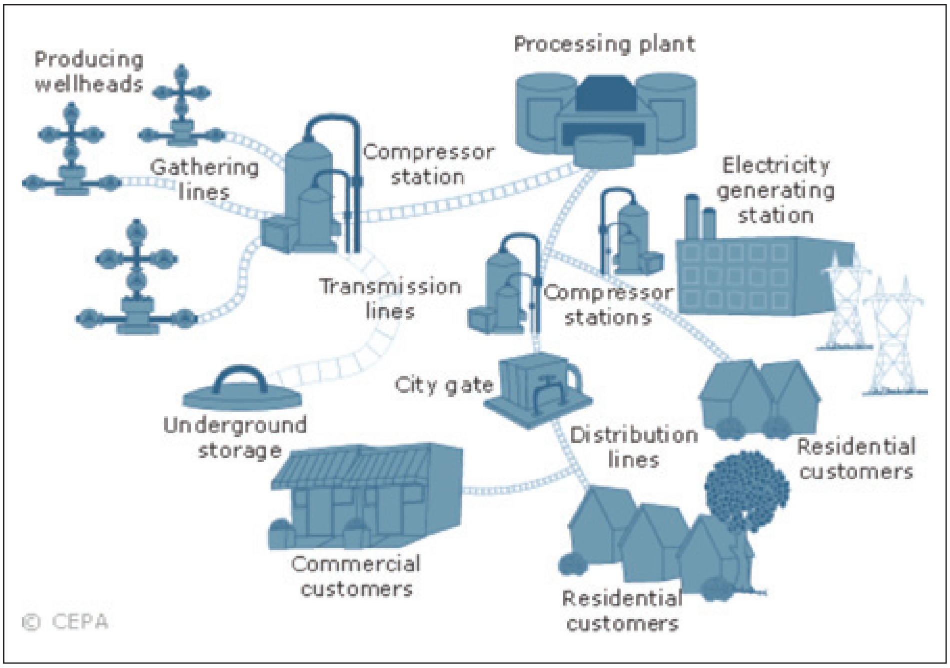


FIGURE 1 Pictogram of natural gas systems. Source: Canadian Energy Pipeline Association (www.cepa.com/about-pipelines/types-of-pipelines/natural-gas-pipelines).

impacts in the western United States. Continuing research to improve the reliability of emission estimation methods is essential to support effective air quality regulation and international emission reporting commitments.

The US Natural Gas System: Scope, Contents, and Controls

The United States has more than 1 million oil and gas wells in operation and close to 500 processing plants, 1,400 compressor stations, and 400 underground storage facilities. There are approximately 20,000 miles of gathering pipelines, 300,000 miles of transmission pipelines, and 2 million miles of distribution pipelines.[1] Major efforts are required to maintain, operate, and monitor such an extensive system—engineers know that even the best-engineered systems can leak. Natural gas can leak from both underground and aboveground sources (some of the migration pathways from wells and other underground origins are discussed by Bachu and Valencia in this issue). In this paper the focus is on natural gas leakage from surface operations and equipment.

Figure 1 is a pictogram of natural gas systems. Gas is extracted at well heads and then moved through a network of gathering lines to compressor stations. After compression, it goes to processing plants that remove contaminants and separate out the natural gas liquids, such as propane and butane. The gas is then sent through transmission lines to power plants, homes, and commercial facilities.

Air quality assessment requires knowledge of the kind of product being moved in different parts of the system in order to characterize the potential content of leaks. Raw natural gas may contain about 70 percent methane, but by the time it is processed and distributed its methane content will be 90 percent or more. And the mix of hydrocarbons in natural gas differs not only between dry gas and wet gas (gas coproduced with oil) but also among geographical basins and even within the same basin. In addition to methane, which is a potent greenhouse gas, natural gas can contain varying amounts of other saturated hydrocarbons (e.g., ethane, propane, butane) as well as hazardous air pollutants such as benzene, toluene, and hydrogen sulfide.

Regulation of the completion of hydraulically fractured natural gas wells currently falls under the separate jurisdictions of states, and consequently results in different operator practices and potentially significantly different levels of emissions. But as of January 2015 operators of fractured or refractured gas wells will have to use reduced emission completions and a completion combustion device to reduce volatile organic compound (VOC) emissions from gas well completion (in accordance with a 2012 EPA rule discussed below).

Figure 2 illustrates two different circumstances of well completion. Figure 2a shows a completed well in Utah in the winter of 2012 with an open-top tank and open pit pond to capture flowback fluids. Over a 3-week span some of the highest methane (>800 ppm) and benzene

[1] These data are from the US Department of Energy's Energy Information Agency (www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/ngpipeline/index.html and www.eia.gov/todayinenergy/detail.cfm?id=8530#) and the US Department of Transportation (www.phmsa.dot.gov/pipeline/naturalgas).

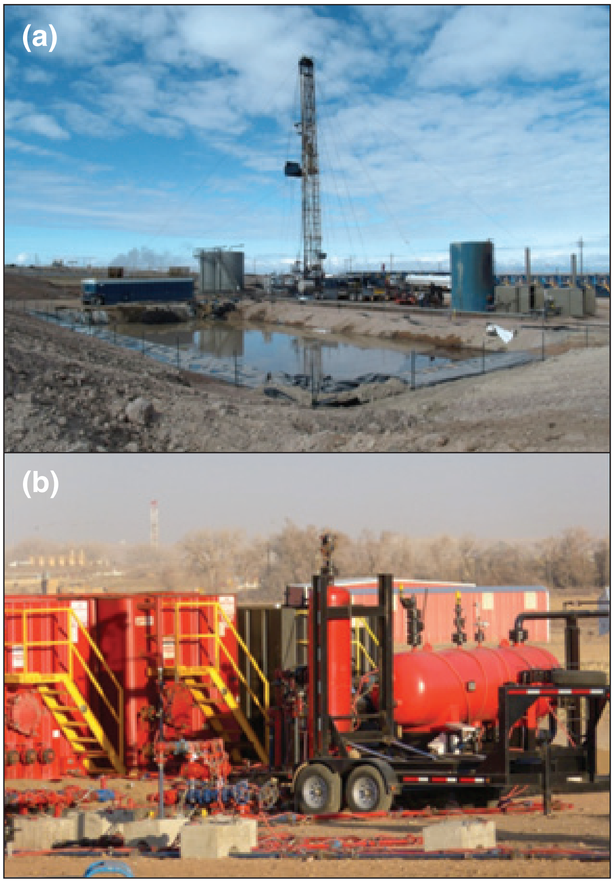


FIGURE 2 (a) Completed well in Utah in the winter of 2012 with an open pit pond (foreground) to capture flowback fluids and a venting open-top tank to the left of the pond. Credit: Gabrielle Pétron. (b) "Green" well completion in Colorado in the spring of 2013 showing separation equipment to capture gases from the flowback fluid. Credit: Gabrielle Pétron.

(>500 ppb) mixing ratios were recorded just downwind of the site on a public road. In comparison, a "green" (reduced emissions) well completion in Colorado (Figure 2b) in the spring of 2013 has equipment that allows an operator to separate and capture the gas from the flowback fluid at the well site close to the time when hydraulic fracturing is completed, often within a couple of days; no substantial methane enhancement was detected at that location.

Global Monitoring of the Atmosphere

Accurate long-term high-quality measurements of the composition of the atmosphere at various locations around the United States can support effective tracking of potentially harmful local and regional alterations. The resulting data can enhance understanding of emissions responsible for air pollution and climate change and how they may change over time. The availability of such data for the scientific community, the public, and decision makers is essential for them to analyze specific events and trends.

The Global Monitoring Division (GMD) of the US National Oceanic and Atmospheric Administration (NOAA) operates a global air sampling and measurement network that is the largest source of well-calibrated observations of the global remote atmosphere composition and how it has changed over the past four decades. GMD is the World Meteorological Organization (WMO) Central Calibration Laboratory, which maintains and distributes the WMO mole fraction calibration scale for several long-lived greenhouse gases, including carbon dioxide and methane. The central calibration scale ensures confidence that, from one sampling location and time to another and from one measurement laboratory to another, consistent well-calibrated datasets are described and compared—apples to apples, methane to methane.

Carbon dioxide is an important trace gas and the main driver behind anthropogenic climate forcing. Observations recorded since 1960 at the Mauna Loa Observatory in Hawaii demonstrate a steady climb of atmospheric CO_2 from about 315 parts per million (ppm) to over 400 ppm in May 2013, a record-breaking figure that caught the attention of the media (Kunzig 2013). In April 2014, the observations at Mauna Loa showed a mean CO_2 level of 401.3 ppm.

GMD has also measured stratospheric ozone at the South Pole for several decades to track the size of the stratospheric ozone hole. In the spring of 2012 the hole was the smallest in the past 20 years, a positive result that shows the global ban on ozone-depleting substances is starting to pay off. More recently, ozone pollution near the surface in oil- and gas-producing regions has been the focus of GMD collaborations with several western states.

Emission Inventories

To assess emissions from the large and complex natural gas industry, regulators break down these systems into emission source categories. Large point sources, such as processing plants and compressors, are usually regulated by the EPA. The large engines used in drilling rigs are regulated at the state level, but regulatory details vary from state to state. Smaller sources include equipment such as heaters, pneumatic devices, dehydrators, separators, and storage tanks for oil, liquid condensate, and produced water. So far, violation of national standards for surface ozone levels in states such as Colorado, Wyoming, and Texas has been the main driver to regulate some of these minor (but numerous) VOC point sources in several counties.

In 2012 EPA signed a rule providing New Source Performance Standards for VOC emissions from new pieces of equipment (e.g., pneumatic controllers, oil and condensate storage tanks) at oil and gas facilities and completion of hydraulically fractured (or refractured) gas wells.[2] Expected to come into effect by early 2015, these national standards for new "small" distributed oil and gas sources address emissions from many potential emission sources and establish minimum requirements for air emission reductions.

To track potential air impacts, an inventory of emission sources and activities from natural gas and/or oil production in a region is usually the first tool developed and used by regulators. Box 1 shows an example of the source categories covered by emission inventories for different producing basins in the Rocky Mountain region.[3] Each item in the inventory is assigned an *emission factor*, the amount of emissions expected from that item over a designated time period, usually a year. Estimates of emissions at the county, state, or national level are derived by combining the inventory of source/activity counts with the appropriate emission factors. These estimates are usually on an annualized basis and include different species of greenhouse gases, VOCs (which can act as precursors of surface ozone), and hazardous air pollutants.

BOX 1
Current Western Regional Air Partnership (WRAP) Oil and Gas Studies Source Categories (in alphabetical order)

- Amine units (acid gas removal)
- Artificial lift engines (pumpjacks)
- CBM pump engines
- Completion and recompletion venting
- Condensate and oil tanks
- Dehydrators
- Drill rigs
- Flaring
- Fugitive emissions
- Heaters
- Large point sources (gas plants, compressor stations)
- Lateral compressor engines
- Miscellaneous or exempt engines
- Pneumatic devices and chemical pumps
- Produced water tanks
- Saltwater disposal engines
- Truck loading of oil or condensate
- Vapor recovery units (VRUs)
- Well blowdowns
- Wellhead compressor engines
- Workover rigs

Source: T. Moore, Western Governors Association (www.wrapair.org/forums/ogwg/documents/2008-08_Phase_III_O&G_Basin_Map_&_Source_List.pdf)

How Accurate Are Emission Estimates?

Emission factor values are a weakness in the system. They are usually derived from a small set of direct measurements by consulting firms or collaborators with the EPA and may be based on data collected as long as 20 years ago. At this time, more than 80 different emission factors are used in the EPA's national inventory for natural gas systems and more than 60 in its oil inventory.

The fact that there are two different EPA inventories—one for natural gas wells and one for oil wells—is a problem in itself. The inventories are each maintained by separate departments and personnel and operate independently with different source categories, emission factors, and schedules for updates and revisions. This arrangement fails to reflect the reality that natural gas and oil can flow from both types of wells.

Furthermore, although the EPA has published a national annual emission inventory since the mid-1990s, the original methods appear to have underestimated actual methane emissions from natural gas production. The agency has been updating some of its methods and information sources since 2011, resulting in higher emission estimates than in the inventory released in 2010, which relied mostly on emission factors from the early 1990s.

But reliance on the current system for estimating emissions is problematic: If the models used are inaccurate, regulatory policies and actions may not be effective. In fact, a very recent study, involving participants from

[2] The rule, signed on April 17, 2012, is available at www.epa.gov/airquality/oilandgas/pdfs/20120417finalrule.pdf. The standards are available at www.epa.gov/airquality/oilandgas/.

[3] Data from the Western Regional Air Partnership's Regional Emissions Data and Analyses, available at http://wrapair2.org/emissions.aspx. The categories are used by Air Quality Program Manager Tom Moore's team at the Western Governors Association.

a number of institutions, indicated that actual methane emissions from natural gas systems in the United States and Canada appear to be larger than the official estimates (Brandt et al. 2014). Even on a smaller scale, there can be serious discrepancies, as discussed below.

Atmospheric Studies

My NOAA/GMD colleagues and I have been conducting extensive research on surface ozone pollution and hydrocarbon emissions in several oil and natural gas basins in Colorado (since 2008), Wyoming (2008), Utah (2012, 2013), and Texas (2013). We use instrumented vans, tethered sondes, balloons, airplanes, and towers to make accurate downwind measurements of emission plumes.

Measurement-based Methane Emission Estimates

Figure 3a is a map showing the Denver-Julesburg Basin (about half an hour from Denver and Boulder), where there are more than 20,000 active oil and gas wells. Figure 3b contrasts levels of methane measured at the upstream edge of the oil and gas basin at the NOAA Boulder Atmospheric Observatory (BAO) (in blue) with those detected at the Platteville site (in red) near the middle of the oil and gas basin. Methane concentrations are clearly much higher in the middle of the field than in the upstream (BAO) location.

The highest (peak) levels are always experienced on nights when there is very little dispersion in the atmosphere. Some peak levels of methane registered at 10 ppm, five times the background value, a level rarely seen that suggests the existence of persistent leaks of natural gas from operations nearby (the peaks have a $\delta^{13}CH_4$ isotopic signature typical of natural gas methane in this region, which is different from the isotopic signatures of methane emitted by landfills and cows).

Figure 3c illustrates the strong correlation between the fugitive (or rogue) gases associated with methane in this same basin. Note the stronger correlation in the northeast direction from BAO (red circles), the sector with the large majority of the wells.

Data show that high methane levels are neither isolated nor few in a number of oil and gas fields. A GMD flight over the Uinta Basin in northeastern Utah in February 2012 revealed a "lake" of enhanced methane over the largely uncommingled but adjacent gas and oil fields, with the gas field showing higher levels (Karion et al. 2013). Here also levels of short-lived hydrocarbons, contributors to the chemical processes that lead to surface ozone production, were significantly correlated with methane levels. There are very few human settlements or cattle in the region; 97 percent of the methane emissions were attributed to oil and gas activities in Uintah County, Utah.

To derive independent emission estimates from measurements obtained from aircraft flights, the aircraft mass balance technique (Karion et al. 2013) is used. The method draws on variables such as air composition, wind speed and direction, and dispersion rates to estimate the fraction of produced gas that is lost to the atmosphere. The mass balance technique does not use assigned standard emission inventory values but

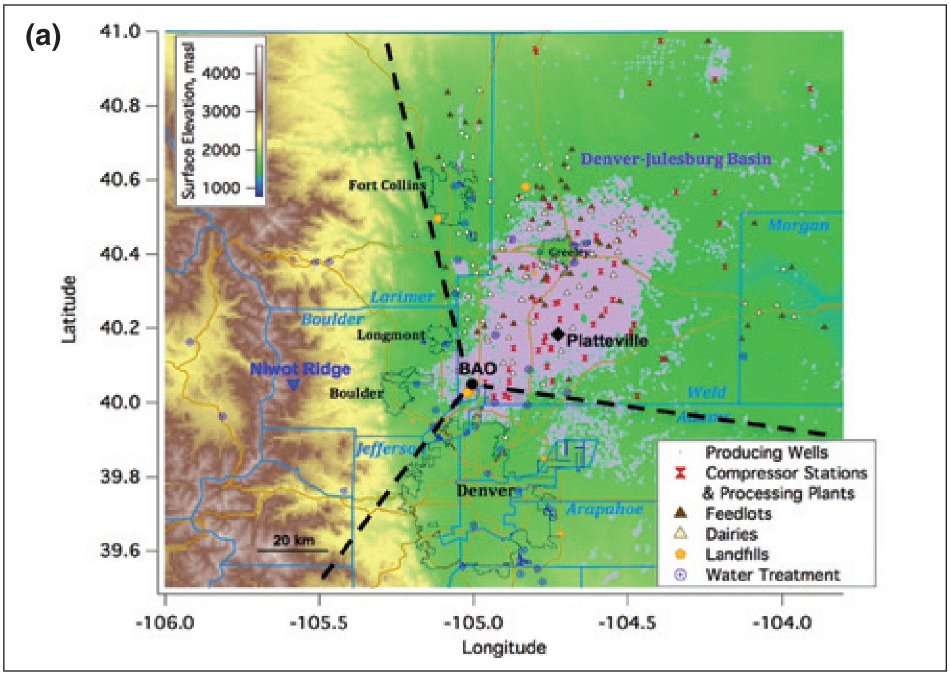


FIGURE 3 (a) Oil and natural gas wells (lavender) in the Denver-Julesburg Basin in northeast Colorado. The dashed black lines indicate three wind sectors with respect to the Boulder Atmospheric Observatory (BAO): northeast, west, and south. The region shown has ~20,000 wells and over 500,000 cattle.

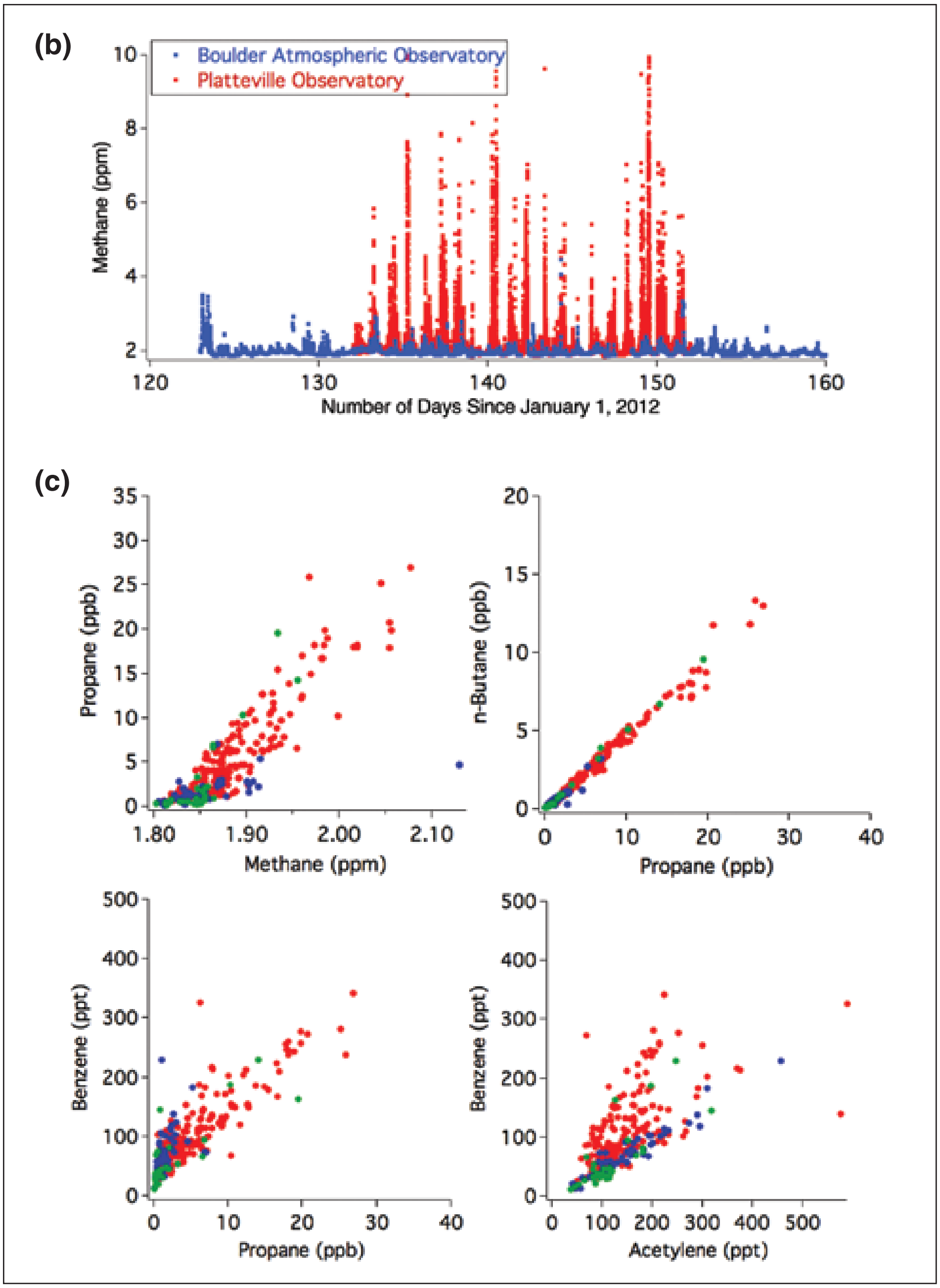


FIGURE 3 (b) Methane levels at the Boulder Atmospheric Observatory (blue) and at the Platteville Observatory (red) in May 2012. Highest levels are observed at night when the planetary boundary layer is shallow and atmospheric mixing is reduced. ppm = parts per million. (c) Correlations of several nonmethane hydrocarbon gases with methane levels in air samples collected 300 meters above ground level at the Boulder Atmospheric Observatory (BAO) in the Denver-Julesburg Basin. The wind sectors with respect to the BAO are indicated in Figure 3a. Methane, propane, and n-butane are all markers of natural gas emissions; acetylene is a marker of combustion sources, such as road traffic emissions. The red circles indicate air samples collected at BAO in air masses from the northeast, where most oil and natural gas production occurs. Correlation between tracers suggests that they have common sources. Note the strong correlation between n-butane and propane. The hazardous air pollutant and carcinogen benzene correlates well with acetylene in the south (blue) and west (green) wind sector samples (urban source) and correlates more with propane in air samples from the northeast (from oil and gas sources). ppb = parts per billion; ppt = parts per thousand.

is based entirely on measurements. As a result, it is possible to obtain numbers for the amount of methane leaked in the atmosphere compared to the amount of natural gas (and methane) produced in a particular basin.

Some regional inventories, such as those developed for oil and gas basins in several western states,[3] have already reported emissions with actual leakage rates higher than the 0.8–0.9 percent estimated by the EPA for natural gas production and processing. Figures for hourly leakage rates in the Uinta and Denver-Julesburg basins based on one or two flights are higher still, nearly double those derived from basin-level inventories for VOC emissions (Karion et al. 2013; Pétron et al. 2012).

While the aircraft surveys are a good way to obtain estimates of the total emission rate from an entire basin, measurements on the ground provide a more detailed identification of specific emission sources. GMD used a specially equipped van to measure concentrations of various air pollutants in the Uinta Basin oil and gas fields in Utah; an example of the data obtained is shown in Figure 4a, and the van's path is shown in Figure 4b. Concentrations near compressor sites were three to five times higher than the background methane level of 2 ppm.

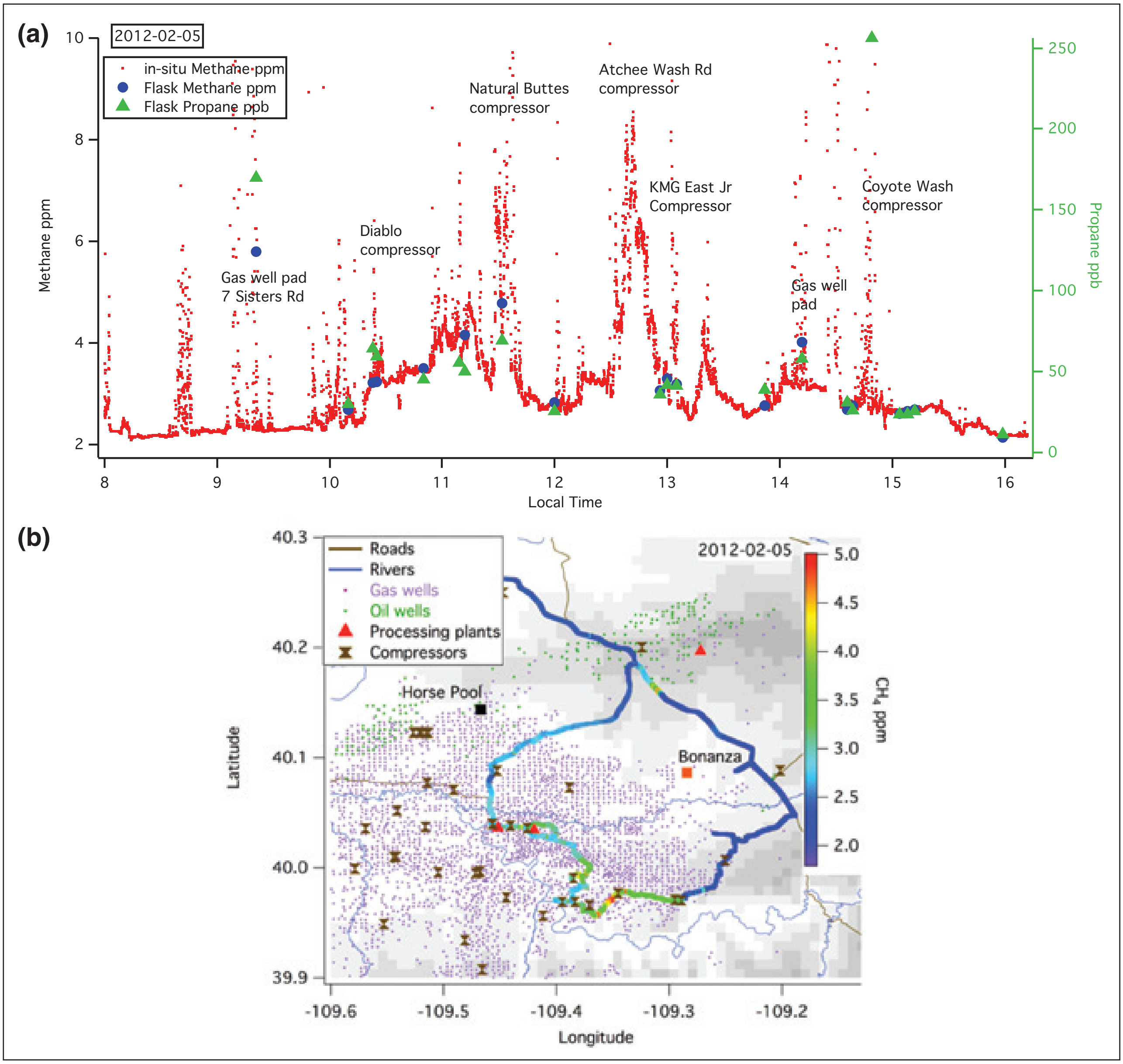


FIGURE 4 (a) Local methane mole fractions obtained during a drive through the Uinta basin in Utah in February 2012. Background methane levels are typically 1.8–1.9 parts per million (ppm) in the wintertime at this latitude (39.9–40.3°N). Note that the size of the mole fraction enhancements downwind of a particular source cannot be interpreted as reflecting the magnitude of that source. Based on the location of a facility, nearby public roads, and local surface winds, the GMD van was positioned to collect air samples in the detected methane plume for chemical analysis of the emission composition. In situ measurements of methane were conducted at 0.5Hz using a Picarro cavity ring down spectroscopic gas analyzer installed in the mobile laboratory. The total uncertainty on the in situ measurements is ±2 ppb. Discrete air samples were also collected in 0.7L borosilicate glass flasks by the mobile lab team for further chemical analysis at the NOAA Boulder Laboratory. (b) Heavy line shows the route taken to obtain data shown in Figure 4a. The route is color-coded (see right-hand bar) with the methane molar fraction measured in situ in the mobile laboratory.

More broadly, anomalously high methane levels were detected downwind of some surface operations in all the oil- and gas-producing regions investigated. In one location in the Barnett field in Texas, GMD gauges revealed methane well above background levels at 5 out of 22 wells, smaller deviations at 8 wells, and no deviation from background at 9 wells. The EPA inventory method assumes that each of these wells will have the same emission magnitudes, and will thus get the total emissions wrong and fail to identify specific problematic sources (high emitters).

Surface Ozone Pollution

Mixtures of volatile organic compounds and nitrogen oxides can react to produce surface ozone. Usually ozone surface pollution is an urban, summertime problem, but it can also occur in remote or peri-urban oil- and gas-producing regions in the winter or summer.

Because natural gas contains other hydrocarbon species in addition to methane, their presence in the atmosphere as rogue gases is highly correlated with methane emissions. When these rogue gases are released in an area of snow-covered ground, low wind, and strong temperature inversions, the result is a "perfect storm" in which the pollutants can react to form ozone. The phenomenon of wintertime surface ozone in remote regions was not anticipated, monitored, or modeled by regulators and scientists.

In Wyoming, Utah, and Colorado, VOC emissions from oil and gas operations contribute significantly to regional ozone pollution in the summer (Colorado) (Gilman et al. 2013) or winter (Wyoming, Utah). We studied (and first reported in 2008) wintertime ozone surface pollution in the Wyoming Green River basin (Schnell et al. 2009) and have investigated similar conditions in Utah's Uinta Basin (Oltmans et al. 2014). For nearly 40 days in January–March 2013, surface ozone levels in this basin exceeded the national ambient air quality standards of 75 ppb (8-hour average). On 11 days the levels rose to 120–140 ppb—levels that are unhealthy for humans. An EPA webpage reports surface ozone pollution in counties in the Rocky Mountain region[4]; all of the ones in nonattainment are in gas- and oil-producing regions.

It is clear that better quantification of actual emissions of methane and VOCs is needed, as well as improved understanding of how such emissions contribute to the formation of seasonal ozone in and near oil and gas fields (Oltmans et al. 2014).

Summary and Conclusions

Atmospheric measurements from vehicle and aircraft platforms are a reliable and quantitative method to detect leaks and estimate emissions from natural gas- and oil-producing regions. Yet the data available also point to the need for additional reliable gauges of methane, VOCs, and hazardous air pollutant emissions from various source types in these regions, both to evaluate and improve (if necessary) the accuracy of emission inventories and to quickly identify problematic high-emitting sources.

As various sectors of the economy strive to reduce their environmental and climate impacts, it is imperative to develop more accurate emission estimation methods. Such methods would increase the reliability of EPA and other inventories used by regulators to guide air quality management decisions, including new emission reduction requirements for specific sources.

Some research is still needed to explore the full potential of different atmospheric measurement techniques, to assess how they might effectively supplement existing leak detection and repair programs for different scales, and to provide an independent assessment of the effectiveness of new emission reduction regulations.

If natural gas is to provide a bridge to a greener future, emissions must be curbed. That can be achieved only with industry leaders, regulators, researchers, and engineers working together using reliable data.

[4]Area Designations for 2008 Ground-level Ozone Standards: Region 8 Final Designations, April 2012. The six states in Region 8 are Colorado, Montana, North and South Dakota, Utah, and Wyoming. Available at www.epa.gov/ozonedesignations/2008standards/final/region8f.htm.

References

Bachu S, Valencia RL. 2014. Well integrity and risk assessment. The Bridge 44(2):28–33.

Brandt AR, Heath GA, Kort EA, O'Sullivan F, Pétron G, Jordaan SM, Tans P, Wilcox J, Gopstein AM, Arent D, Wofsy S, Brown NJ, Bradley R, Stucky GD, Eardley D, Harriss R. 2014. Methane leaks from North American natural gas systems. Science 343:733–735.

Gilman JB, Lerner BM, Kuster WC, de Gouw JA. 2013. Source signature of volatile organic compounds from oil and natural gas operations in northeastern Colorado. Environmental Science and Technology 47(3):1297–1305.

Karion A, Sweeney C, Pétron G, Frost G, Hardesty RM, Kofler J, Miller BR, Newberger T, Wolter S, Banta R, Brewer A, Dlugokencky E, Lang P, Montzka SA, Schnell R, Tans P, Trainer M, Zamora R, Conley S. 2013. Methane emissions estimates from airborne measurements over a western United States natural gas field. Geophysical Research Letters 40:4393–4397.

Kunzig R. 2013. Climate milestone: Earth's CO2 level passes 400 ppm. National Geographic News, May 9. Available at http://news.nationalgeographic.com/news/energy/2013/05/130510-earth-co2-milestone-400-ppm/.

Oltmans S, Schnell R, Johnson B, Pétron G, Mefford T, Neely R III. 2014. Anatomy of wintertime ozone associated with oil and natural gas extraction activity in

Wyoming and Utah. Elementa Science of the Anthropene 2, doi:10.12952/ journal.elementa.000024.

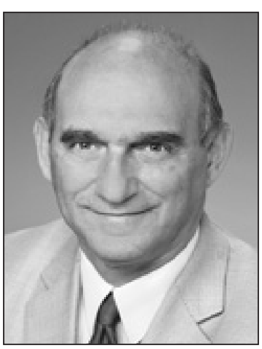
Pétron G, Frost G, Miller BR, Hirsch SA, Montzka A, Karion M, Trainer C, Sweeney AE, Andrews L, Miller J, Kofler A, Bar-Ilan EJ, Dlugokencky L, Patrick CT, Moore TB Jr, Ryerson C, Siso W, Kolodzey PM, Lang T, Conway P, Novelli K, Masarie B, Hall D, Guenther D, Kitzis J, Miller D, Welsh D, Wolfe W, Neff P. 2012. Hydrocarbon emissions characterization in the Colorado Front Range: A pilot study. Journal of Geophysical Research D, Atmospheres 117: D04304.

Schnell RC, Oltmans SJ, Neely RR, Endres MS, Molenar JV, White AB. 2009. Rapid photochemical production of ozone at high concentrations in a rural site during winter. Nature Geoscience 2:120–122.

Risks associated with multistage horizontal wells used for hydraulic fracturing are limited and their impacts are mitigated by improvements in design, construction, and monitoring.

Well Integrity

Challenges and Risk Mitigation Measures



Stefan Bachu

Randy L. Valencia

Stefan Bachu and Randy L. Valencia

Hydraulic fracturing is not a new technology—it has been practiced in vertical wells by the oil and gas industry since the late 1940s–early 1950s. But multistage hydraulic fracturing in horizontal wells, which may be a few miles in length, opened new possibilities for producing oil and gas from tight reservoirs and methane-rich shales. The subsequent recent surge in horizontal drilling and hydraulic fracturing has sharpened concerns about risks of fracture propagation, contamination of other resources, including groundwater, by frac fluid and/or methane, and interwellbore communication between the injection well and an offset well, resulting in either production of frac fluids or loss of integrity of the offset well, as summarized in Table 1.

Because of public concern about the impacts of horizontal drilling and hydraulic fracturing on possible groundwater contamination, we show that vertical propagation of fractures from the producing formations is rarely a source of such contamination; instead, surface activities are the major source of groundwater contamination (Kell 2011; King and King 2013; Krupnick et al. 2013). For example, handling and storage of injection and produced water were documented as the predominant source of groundwater contamination in a study of more than 317,000 wells in Texas and Ohio (Kell 2011).

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TABLE 1 Issues in shale gas production identified by regulatory agencies

Surface issues	• Land access • Traffic and noise • Water resources • Handling and storage of injection and produced water (this is the main source of groundwater contamination)
Subsurface issues	• Integrity and zonal isolation of injection wells • Induced microseismicity • Fracture propagation • Contamination of other resources, including groundwater, by frac fluid and/or methane • Interwellbore communication between the injection well and an offset well, resulting in either production of frac fluids or loss of integrity of the offset well

Our focus in this article is on the risks associated with subsurface operations, particularly wells, involved in fracturing low-permeability shales to release natural gas. We draw on recent analyses of well design and construction, gas leakage, and associated geological factors in the United States and Canada, collected by regulatory agencies, academics, and operators (Kell 2011; King and King 2013).[1]

We begin with a review of challenges and questions that have emerged with the expansion of hydraulic fracturing. We then provide, as background, an overview of the construction and components of a horizontal well. The following sections address the challenges and questions raised below, and we conclude with suggestions of measures to mitigate potential hazards associated with hydraulic fracturing and horizontal wells.

New Challenges and Questions

The unprecedented development of shale gas resources poses significant questions for the public, regulators, and the industry:

1. What new risks to the integrity of existing wells are inherent in the advanced technologies of horizontal drilling and hydraulic fracturing, and how are those distinct from conventional oil and gas development?
2. What are the potential risks to well integrity (Kell 2011; King and King 2013; Krupnick et al. 2013) that may threaten groundwater supplies and how serious and likely are those risks? Although any contamination of groundwater occasioned by drilling and fracturing techniques and operations may be serious, how do the risks of contamination from horizontal drilling and hydraulic fracturing compare to other threats to groundwater?
3. What geological conditions or perturbations might impinge on well development and on gas migration to groundwater, and how might they be addressed?
4. Are there new mitigation measures that need to be adopted in engineering practices and regulatory standards and oversight?

Overview of Well Design and Construction

Before reviewing the specifics of well design and construction, we explain the concept of *well integrity*. Well integrity encompasses the technical, operational, and organizational solutions necessary to reduce the risk of uncontrolled release of gas and hydrocarbon fluids throughout the life cycle of a well.

Protective Well Design

Wells are typically designed from the inside out and constructed from the outside in. Structural elements termed *well barriers* are essential in both the design and construction of wells. These barriers function as containment envelopes to prevent unintentional fluid flow between the geological unit from which the well produces and other geological formations, reservoirs, shallow groundwater used for drinking water, and/or the atmosphere. The barriers have built-in redundancies to reduce the risks that gases or liquids can escape from a well anywhere along its length, enter a well from untargeted zones, or migrate from one geological zone to another.

On its way to the target zone (e.g., a gas-bearing shale), a well traverses other geological layers, impermeable as well as more permeable, such as sandstone, coal, and carbonates containing various hydrocarbons and brines. If fluid escapes containment, it follows a *leakage pathway* to reach an adjacent permeable formation or the environment (Watson and Bachu 2008).

To maintain well integrity and prevent impacts from such leaks, *zonal isolation* is among the key functions of

[1] The types and comprehensiveness of data available on well characteristics, performance, and failures are uneven but became increasingly detailed in the latter part of the 20th century.

well barrier design. Introduction of improvements in well tubing and pipes, cementing design and practices, couplings, pressure controls, and plugging design and practices are among many examples of technologies undertaken, in part, to sustain the integrity of a well during its active life and after abandonment.

Construction

Wells must be of the right size and materials to withstand their environment. An exposed and corrodible iron pipe inserted into a borehole will not do.

Typically, the interior or production casings of a well consist of steel pipes or tubes designed to withstand the pressure, temperature, and chemical environment of both the produced fluids that come into the well and the fluids (usually brines but also gas) on the outside of the well in case the borehole is not fully cemented or the cementing job is deficient.

Once the interior casing design of a well is determined, the exterior casing size, strength, and cements can be designed around it. A series of concentric casings is fitted into a wellbore and cemented sequentially as they are set in place when a well is drilled, finally looking much like an extended telescope. Cements are poured between each layer of casing and between the casing and the borehole to stabilize the well structure and to provide an impermeable barrier between geological zones. The well design is thus a series of nested barrier elements that provide structural strength, barriers to fluid flow, and pressure containment.

The number of casings and cement barriers differs according to the depth in the well. Shallow portions of the well (500–1,500 ft) can have up to 4 or more barrier elements depending on regional geology and regulatory requirements to protect groundwater. Intermediate depths of the well may have up to 2 barrier elements, and deep sections commonly have 1 or 2 barrier elements.

Cement, Couplings, and Other Safeguards

Cement is an important contributor to well integrity. It is used not only to sheath well casings but also to plug zones to prepare a well for abandonment.

Cement must meet four criteria to serve as an effective barrier: (1) there must be a sufficient amount for the task; (2) it must have the proper quality and properties after setting; (3) it must be free of voids, fractures, and/or channels; and (4) there must be a robust bond with the pipe and with the rock formations on the outside.

The quality of the cement is more important than the volume used. Attention to the cement composition is essential because some additives, such as bentonite or gypsum, deteriorate in the presence of CO_2 or under acidic conditions, potentially opening leakage pathways (Watson and Bachu 2008, 2009).

Cement bonding logs are used to assess isolation and pressure containment, but have frequently been found to be inaccurate. Isolation of zones can be measured effectively only with pressure tests (King 2012).

Additional well components enhance integrity and serve as barriers. For instance, improvements in threaded couplings and in coupling preparation have greatly reduced leaks from joints. Valve configurations (called "Christmas trees" because of their shape) at the top of a wellhead control well pressures and flow rates in a variety of well conditions.

Annular flows of gas at the surface, often signaled by rising pressures, can indicate barrier problems anywhere

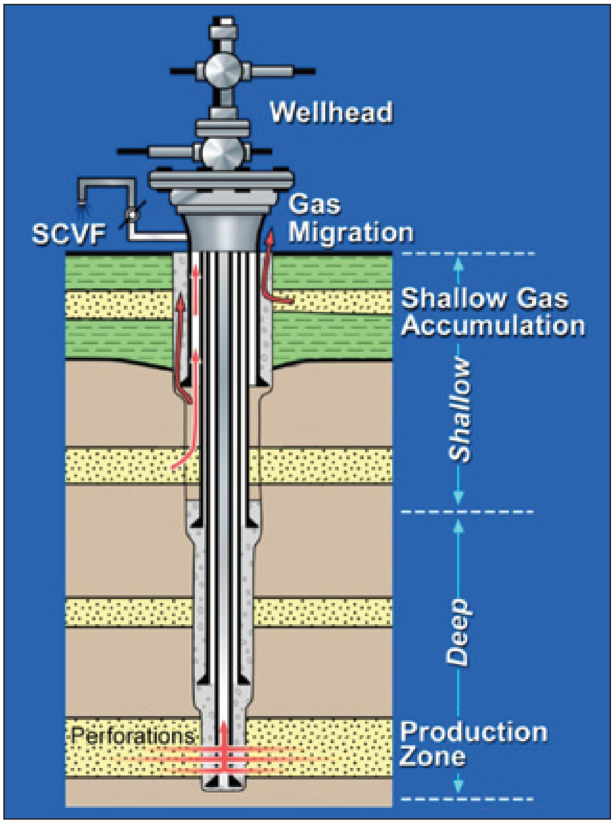


FIGURE 1 Schematic diagram of vertical well showing concentric steel casings (solid black vertical lines) and cement barriers (adjacent grey with "pebbles"). Gas migration from shallow gas-containing formation and surface casing vent flow (SCVF) is shown.

in the well. In old wells, visible gas migration may be manifested as bubbles rising in puddles surrounding the well (Bachu and Watson 2006). Gas migration and surface casing vent flow leakage are illustrated in Figure 1, a schematic of typical vertical well construction. Gas accumulating inside the casing leads to pressure buildup, also known as *sustained casing pressure*. In Canada, venting of the accumulated gas is allowed in order to avoid pressure buildup that may damage the well; depending on the rate of the vent flow and severity of the leak, the operator may be required to repair the well immediately or the repair may be delayed until well abandonment.

TABLE 2 Development of drilling wells and the potential for pollution, 1830–2008

Year(s)	Well construction and completion norms	Potential for pollution
1830–1916	Cable tool drilling, no cement isolation, wells vented	High
1916–1970	Cement isolation steadily improving	Moderate
1930s	Rotary drilling replaces cable tool, pressure control systems developed	Moderate
1952	Hydraulic fracturing becomes commercial	Lower from frac aspects
1960	Gas-tight couplings and joint makeup improvements	Moderate
1970	Introduction of horizontal wells, cement improvements	Lower
1988	Multifrac, horizontal wells, pad drilling reduce environmental land footprint up to 90%	Lower
2005	Well integrity assessments, premium couplings, additional barriers, and cementing full strings	Lower after 2008–2010
2008	Real-time well integrity needs being studied to achieve early warning and problem avoidance	Lowest yet

Source: King and King (2013).

When wells are closed or abandoned, additional safeguards are required to avoid leakage from or migration into a well. Cement plugs or other mechanical barriers in various configurations placed above a zone impede fluid flow through a well, but these too are subject to degradation or failure, especially in older and abandoned wells.

In addition to these physical measures, a host of technologies and procedures now enable not only periodic monitoring but also real-time identification of issues before they jeopardize well integrity. Among these technologies are gas and pressure monitors, gas chromatography, and acoustic, sonic, temperature, and electronic sensors. Many of these have been implemented in response to state and provincial regulations.

Risks to Well Integrity

There are many reasons why barriers fail and well integrity is threatened. Pipes and casings can corrode, cement can chemically or mechanically degrade, valves can fail or leak, and well maintenance may be faulty. The probability of failure is strongly related to the type and age of a well.

Old and New Wells

Table 2 shows the qualitative evolution of well construction since 1830 (King and King 2013), and Table 3 gives data on recorded well failure rates (Kell 2011). Notably, hydraulically fractured wells, especially those of recent vintage, are the least likely to develop problems, because of improved construction and barrier standards and more stringent regulatory requirements. Wells built in other periods, however, are vulnerable, especially as they age.

According to a recent study of nearly 65,000 wells in Ohio (Kell 2011), 31,000 drilled before 1983 had a *barrier failure* frequency (with no leak to the environment) of 0.1 percent, whereas the failure frequency for those drilled between 1983 and 2007 was 0.035 percent. During the 25-year study, 0.06 percent of the entire study population of 64,830 wells had a leak to the environment (*well integrity failure*). The same study of 253,000 wells in Texas showed a similar decrease in well integrity failures between newer wells (~0.004 percent) and older wells (~0.02 percent).

The greater propensity of older wells to leak or fail has consequences for new drilling, whether conventional or horizontal, in older fields. Detailed

TABLE 3 Sample data from well studies

Location	Number of wells	Barrier failure frequency (with containment)	Well integrity failure frequency (with a leak path)	Leaks to groundwater
Ohio	64,830	0.035% in 34,000 wells from 1983 to 2007 0.1% in wells before 1983	~0.06% for all wells studied over entire study period, 1983–2007	0.02% (12 wells)
Texas	253,090	0.02%	older wells 0.02% newer wells 0.004% total range, 1993–2008	Producers 0.005%–0.01% Injectors 0.03%–0.07%

Source: Kell (2011). (Other well study data are in King 2012, King and King 2013.)

discussions of well failures are in King (2012) and King and King (2013).

Horizontal Wells and Hydraulic Fracturing

Some well integrity issues are specific to horizontal wells. When the wellbore and casing are turned laterally and proceed horizontally through shale rock, they are subject to gravity along the full lateral length of the pipe. This may make it difficult to keep the pipe properly centered to effectively cement it in place. It will then tend to sag in the unset cement, occasionally leading to a defective cement job and compromising the integrity of the well, particularly during high-pressure fracturing. Repeated pressure changes along the horizontal length of pipe induce stress in the casing and cement and may cause the cement to debond from its casing and crack.

Of greater potential consequence are the possibilities that hydraulic fracturing along a horizontal well will affect nearby offset wells through fractures propagated through the shale. Prediction of fracture length is still a challenge. It is possible for induced hydraulic fractures to contact adjacent wellbores and thereby create a pathway for fracturing fluid and/or gas migration. This may be particularly problematic with historic abandoned wells that lack barrier protections. Similarly, the drilling of offset wells, whether conventional or horizontal, can affect the integrity of horizontal wells when a communicating fracture zone is intersected.

In a study of 5,349 horizontal wells drilled in Alberta and British Columbia from 2009 to 2012, there were 39 reported instances of interwell communication (it is worth noting that fracturing fluid, not methane gas, travelled through the fracture to the offset well and came up the well) (Kim 2012). Because fracture propagation is substantially confined to the shale formation in which it is induced, 95 percent of interwell communication occurred between horizontal wells drilled into shared formations. The distance between the communicating wells averaged about 1,300 feet, but varied from ~90 to ~7,000 feet.

However, the number of horizontal wells completed with multistage fracturing is comparatively very small and the number of conventional wells very large (a ratio of 0.03 percent in North America), so there are no data on how induced fractures may affect broader arrays of nearby conventional offset wells as the frequency of horizontal drilling increases. This uncertainty is compounded when the types and locations of historic offset wells are unknown or their ownership is distributed among different parties.

The Role of Geological Conditions

What happens to the gases and other hydrocarbons released from fractured rocks and to the fracturing fluids injected in them? Can vertical fractures find their way to the surface and serve as pathways for gas to contaminate groundwater?

Horizontal drilling is conducted 4,000 to 13,000 feet below the Earth's surface, below the maximum depth of underground sources of drinking water or protected groundwater (the depths of such sources vary regionally from hundreds to thousands of feet below the surface). Although there are a number of other ways in which methane from below the surface can reach and contaminate groundwater, recent studies of deep horizontal well fracturing indicate that it is nearly impossible for induced fractures to travel through several thousand feet of rock (Fisher and Warpinski 2012; King 2012). Fluids injected into shale plays may dissipate quickly into the rock (sometimes "thieved" by more permeable overlying strata), the extent of flow may be limited by diminishing hydraulic forces, and migration may be localized to the well site except in the possible presence of nearby offset wells (Fisher and Warpinski 2012; King 2012). Meta-analyses of thousands of actual measurements and hundreds of studies on wells drilled in various shale gas basins, combined with more simplistic models of fracture propagation in specific locales, demonstrate that vertical fractures encounter a number of barriers in the complexity and mechanics of layered sedimentary structures.

Shale plays vary both from basin to basin and within a basin in a number of parameters, including the maximum height of induced vertical fractures. The great majority of land-based vertical fractures generally propagate several hundred feet, although a few—in the Barnett and Marcellus shales, for example—have vertical extensions of 1,000–1,500 feet and in some cases even more.

Different geomechanical properties can be encountered in offshore drilling. Studies off the coasts of Mauritania, Namibia, and Norway demonstrate that natural faults and possible stimulated fractures may reach up to 3,000 feet vertically, although the probability of either stimulated or natural fractures exceeding 1,000 feet both on land and under the seabed combined is estimated to be less than 1 percent (e.g., Davies et al. 2012).

Variations underscore the need to adapt drilling and hydraulic fracturing to local conditions and to maintain sufficient depths (2,000–3,000 feet) below groundwater levels to eliminate the possibility of direct contamination from the fracturing process.

Conclusions and Authors' Recommendations

Horizontal drilling and multistage hydraulic fracturing pose limited risks for groundwater contamination in and of themselves (Kell 2011; King and King 2013). Surface activities present greater hazards either from gas leakage into the atmosphere or groundwater contamination associated with fracturing fluids and/or produced fluid handling at the surface.

The potential for any significant long-term hazards of interwell communication between horizontal wells and abandoned or closed older wells can be addressed through adequate regulation. Horizontal multistage fracturing should be conducted (1) at safe depths—2,000–4,000 feet below the base of groundwater protection and based on local geological conditions; (2) at safe distances from offset wells, whether shale gas or vertical wells drilled for other purposes; and (3) at safe distances from abandoned offset wells. In addition, (4) fractures should be designed and controlled to remain within the shale gas–producing formation and not propagate vertically into adjacent formations, reservoirs, or deep saline aquifers.

References

Bachu S, Watson TL. 2006. Possible indicators for potential CO_2 leakage along wells. In: Proceedings of the 8th International Conference on Greenhouse Gas Control Technologies. Gale J, Rokke N, Zweigel P, Svenson H, eds. Oxford: Elsevier.

Davies RJ, Mathias SA, Moss J, Hustoft S, Newport L. 2012. Hydraulic fractures: How far can they go? Marine and Petroleum Geology 37:1–6.

Fisher K, Warpinski N. 2012. Hydraulic-fracture height growth: Real data. SPE 145949 Production and Operations 27:8–19. Presentation at the SPE Annual Technical Conference and Exhibition, Denver, October 30–November 2, 2011.

Kell S. 2011. State oil and gas agency groundwater investigations and their role in advancing regulatory reforms. A two state review: Ohio and Texas. Presentation to Ground Water Protection Council, Oklahoma City, August.

Kim T. 2012. Overview of interwellbore communication incidents: An ERCB perspective. Paper presented at the SPE Canadian Unconventional Resource Conference, October 30–November 1, Calgary.

King GE. 2012. Hydraulic fracturing 101: What every representative, environmentalist, regulator, reporter, investor, university researcher, neighbor, and engineer should know about estimating frac risk and improving frac performance in unconventional gas and oil wells. SPE 152596.

King GE, King DE. 2013. Environmental risk arising from well construction failure: Difference between barrier and well failure, and estimates of failure frequency across common well types, locations and well age. SPE 166142 Production and Operations 28:323–324.

Krupnick A, Gordon H, Olmstead S. 2013. Pathways to Dialogue: What the Experts Say about the Risks of Shale Gas Development. Washington: Resources for the Future.

Silva JM, Gettings RM, Kostedt WL, Watkins VH. 2014. Produced water from hydrofracturing: Challenges and opportunities for reuse and recovery. The Bridge 44(2):34–40.

Watson TL, Bachu S. 2008. Identification of wells with high CO_2-leakage potential in mature oil fields developed for CO_2-enhanced oil recovery. SPE Improved Oil Recovery Symposium, Tulsa, Oklahoma. SPE 112924.

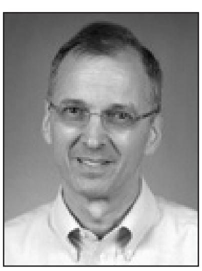
Watson TL, Bachu S. 2009. Evaluation for gas and CO_2 leakage along wellbores. SPE 106817. Drilling & Completion 24:115–126.

Implementation of water and salt recovery is still in its infancy, but solutions exist that are both technically and economically feasible.

Produced Water from Hydrofracturing

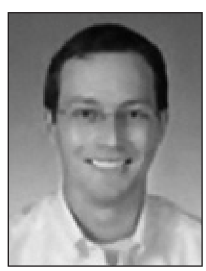
Challenges and Opportunities for Reuse and Recovery

James M. Silva, Rachel M. Gettings, William L. Kostedt, and Vicki H. Watkins



James M. Silva

Rachel M. Gettings



William L. Kostedt

Vicki H. Watkins

Technological advances in exploration and production have enabled the economical production of natural gas from shale, which has led to dramatic increases in both shale gas production and reserves. A key challenge associated with this production is the management of the resulting *produced water*, which is considered a waste product. In Pennsylvania, site of the Marcellus shale, the near absence of salt water disposal facilities has led to the recycling and reuse of about 90 percent of the state's produced water as blendstock for hydrofracturing subsequent wells. However, as well fields mature, the supply of produced water is expected to exceed demand.

James M. Silva is a senior chemical engineer, Rachel M. Gettings a lead chemical engineer, William L. Kostedt a lead environmental engineer, and Vicki H. Watkins a senior chemist, all at the General Electric Global Research Center in Niskayuna, New York.

Thermal water and salt recovery present opportunities to extract value from this produced water. For a "design case" produced water (based on a Marcellus produced water survey), about 55 percent water recovery is possible with evaporation alone, which requires only a simple pretreatment process (the design case is detailed in Silva et al. 2012). High (e.g., 90+ percent) water recovery methods generate a solid NaCl product. Marcellus produced water has relatively high barium and radium content and thus requires further pretreatment to remove these species before NaCl crystallization.

Based on a Marcellus produced water composition survey and a simple material balance, some Marcellus pretreatment waste sludges require disposal as naturally occurring radioactive material (NORM) waste. Economical and environmentally sound options are available, however, for high water and salt recovery from many of these challenging waters.

TABLE 1 Drilling activity and water management, Marcellus and Barnett shale plays, 2012

	Marcellus (Pennsylvania)	Barnett (Texas)
Drilling water, MM[a] gal	0.085[b]	0.25[b]
Hydraulic fracturing water, MM gal	5.5[b]	3.8[b]
New horizontal wells drilled	1,365[c]	660[e]
Wells completed	540[c]	500 (est.)
Active horizontal wells	3,680[c]	>10,000[e]
Wastewater produced, MGD	3.1[c]	2 (est.)
Fraction of wastewater recovered (distilled)	~0.01[c]	0.01 (est.)
Source water availability	Abundant	Scarce
In-state salt water disposal wells	8[d]	12,000[f]
Fraction of wastewater reused	0.87[c]	0.05[g]
Fraction of wastewater deep-well injected	0.12[c]	0.94

[a] MGD = million gallons per day; MM = million; wastewater = flowback and produced water
[b] Mantell (2011).
[c] www.paoilandgasreporting.state.pa.us/publicreports/Modules/DataExports/DataExports.aspx.
[d] Gaudlip (2010).
[e] www.rrc.state.tx.us/barnettshale/barnettshalewellcount_1993-2013.pdf.
[f] McCurdy (2011).
[g] Nicot et al. (2012).

Introduction: Two Shale Gas Plays

We consider two shale gas plays: the Marcellus (Pennsylvania portion) and the Barnett (Texas). The full Marcellus, underlying five states and covering about 95,000 square miles, has the potential to become the world's second largest gas field (Considine et al. 2010). The Barnett, which underlies 14 counties in the Dallas-Fort Worth area, covers about 5,000 square miles. Both plays are 5,000–8,000 feet below the earth's surface, with a shale layer thickness of 100–500 feet.[1]

As shown in Table 1, there are many similarities in water management between the Pennsylvania (PA) Marcellus and the Barnett. For example, both plays use comparable amounts of water for drilling and hydraulic fracturing. Although the Marcellus saw more drilling activity in 2012, both plays had roughly the same number of well completions during this period. (Since the Barnett started development almost 20 years before the PA Marcellus, it has a higher number of active horizontal wells.) Both plays have comparable rates of wastewater generation, and in 2012 only about 1 percent of wastewater was recovered (as distilled water) in each.

There are also sharp contrasts between the two plays. Fresh water is abundant in the Marcellus but scarce in the Barnett. The PA Marcellus has only eight Class II injection wells (also referred to as underground injection control, or UIC, wells) for salt water disposal, with a total disposal capacity of about 0.3 million gallons per day (MGD). In contrast, the Barnett has a large number of high-capacity wells (1 MGD typical), owing to the fact that it overlies the Ellenburger formation,

[1] Specific data are currently available from the company involved in development of these shale plays; for Barnett, www.halliburton.com/public/solutions/contents/Shale/related_docs/Barnett.pdf; for the Marcellus, www.halliburton.com/en-US/ps/solutions/unconventional-resources/shale-gas-oil/shale-plays/marcellus-shale.page?node-id=hgjyd46z.

which has porous rock containing naturally occurring salt water. In 2012, 87 percent of the PA Marcellus wastewater was reused in subsequent well completions; 12 percent was deep-well injected. The opposite was true for the Barnett—94 percent was deep-well injected and 5 percent reused.

Water recycling and reuse has been adopted as a best practice by producers in the PA Marcellus because it is considerably less expensive and much more environmentally sound than hauling large amounts of produced water from eastern Pennsylvania to Ohio, where the nearest site for deep-well injection is located. Further, field reports show that using a blend of produced and fresh water does not negatively impact either the formation or gas production (Minnich 2011). In fact, one report shows that wells completed with a blend of fresh and recycled produced water are among the company's top gas producers (Gaudlip 2010).

The focus of this paper is produced water recovery in the PA Marcellus, because of both the challenging composition of the water and the near absence of in-state UIC disposal capacity.

Management of Produced Water

Completion of a well typically requires approximately 5 million gallons of water, whether from fresh (e.g., municipal or surface water) or brackish water sources. Depending on the shale play, the source water may also include treated flowback and produced water from earlier well completions.

Chemicals—primarily friction reducer, biocide, and acid—are added to the water, which is pumped under pressure into the well. Friction reducer lowers pressure losses in the tubing that carries the water to the shale layer, biocide kills bacteria that can corrode the well tubing, and acid clears cement debris and carbonate minerals from the wellbore. When the shale rock starts to break, graded sand (proppant) is added to the water being injected to keep the cracks and fissures open so that the gas trapped in the rock can flow into the well.

Once the well has been hydraulically fractured, some of the water returns as flowback. For the Marcellus, about 20 percent of the source water returns as flowback within about 30 days, at rates of 300–8,000 barrels (bbl) per day during the first two or three weeks (King 2012). The flow then slows considerably, to about 5–10 bbl/day of produced water, a rate that continues for the lifetime of the well.

This flowback/produced water (also called wastewater or brine) can be disposed of by one of the following methods. It can be deep-well injected into Class II disposal wells, recovered as clean water and solid sodium chloride salt, or treated and reused as blendstock for the next well completion. The latter, which we discuss in the following section, is by far the least expensive alternative.

Treatment and Reuse

The feasibility of produced water reuse hinges on the ability to create a blend of produced and fresh or brackish water that enables effective and economical well completion. Therefore, the composition of the produced water, the fresh/brackish water, and the target blend must be known.

Table 2 shows representative compositions for each of these waters. The design case produced water is based

TABLE 2 Water compositions (all quantities mg/L unless noted)

Component	Design case produced water	Fresh water	Target blend for reuse
TDS[a]	132,000	165	<50,000
Na^+	35,000	6.5	7,800
Cl^-	78,000	13	21,000
Mg^{++}	800	8.1	240
Ca^{++}	9,500	36	2,560
Sr^{++}	2,500	NR	745
Ba^{++}	6,200	NR	1,815
Fe^{++}	50	0.02	37
HCO_3^-	<5	119	150
$SO_4^=$	<5	22	<90
TSS	250	NR	365
TOC	100	NR	not critical
^{226}Ra (pCi/L)	5,000	<5	not critical

[a] NR = not reported; TDS = total dissolved solids; TOC = total organic carbon; TSS = total suspended solids

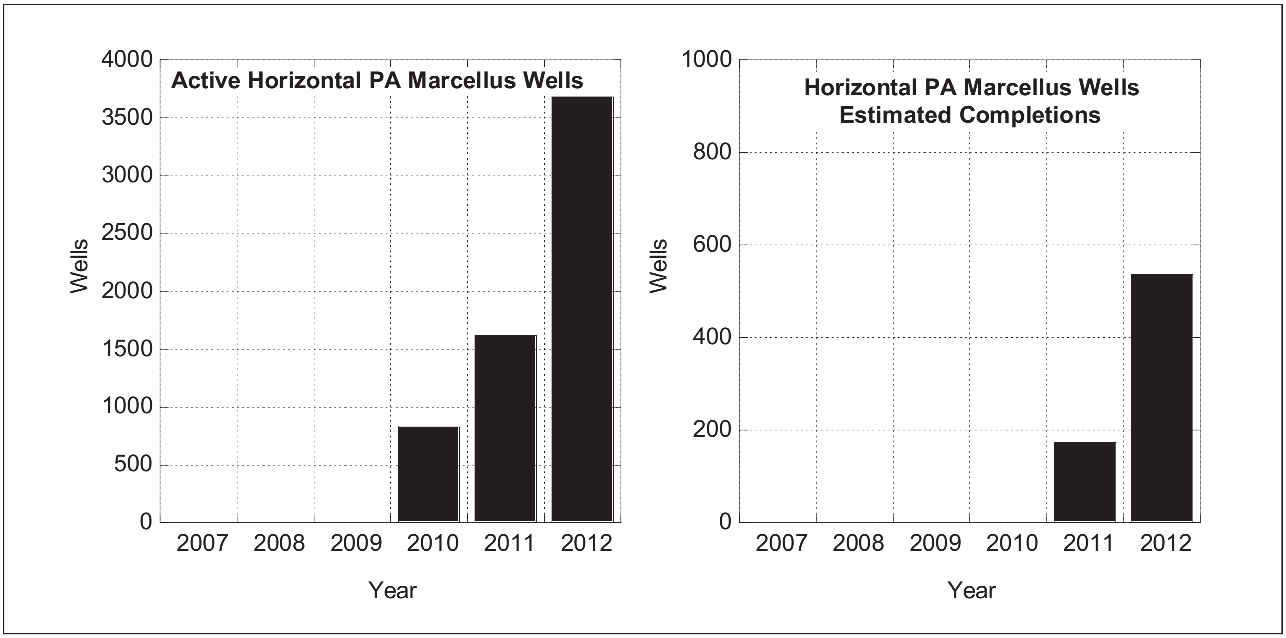


FIGURE 1 Pennsylvania (PA) Marcellus horizontal gas well activity.

on a PA Marcellus survey that indicates the presence of significant hardness, as well as barium (Ba) and radium-226 (^{226}Ra), a naturally occurring radioactive material (Silva et al. 2011). Although NORM is not a radiation hazard at the levels present in produced water, it must be considered in water treatment and recovery processes (discussed below). The produced water also includes suspended solids, organics, and bacteria. Fresh water is represented by a typical river water composition (Snoeyink and Jenkins 1980, p. 6), and the target blend composition is based on a case study reported by Minnich (2011).

Produced and fresh water are both treated for reuse with well-known techniques to remove iron, suspended solids, hardness, and bacteria; this treatment typically involves chemicals (e.g., lime/soda softening, sulfate treatment) and filtration. The treatment of one or both waters is necessary (1) to avoid $BaSO_4$ precipitation, because produced water contains barium and fresh water contains sulfates (see Table 2), and (2) to ensure that the blend composition supports proper functioning of the hydraulic fracturing chemistry (e.g., friction reducers); the blend hardness is typically kept below about 1,000 mg/L, although for one case study it exceeded 2,500 mg/L (Minnich 2011).

Various methods are used to treat produced water for reuse. For example, one water treatment service provider removes iron, suspended solids, strontium, and barium, then returns the treated water to the customer for reuse. Another uses gravity settling with optional filtration to remove suspended solids before blending the produced and fresh water. Because water chemistry varies significantly among sources, treatment for reuse must be specified on a case-by-case basis.

Supply and Demand

The ability to reuse produced water depends on its supply and demand. The *supply* of shale gas–produced water in a given geographical area increases with both the active well count and the rate of well completions in that area. In the PA Marcellus, each active horizontal (also called unconventional) well yields 5–10 bbl/day of produced water, and each well completion yields about 1 million gallons within a month of the hydraulic fracturing activity. Figure 1 shows the estimated number of active horizontal wells and annual well completions in the PA Marcellus, based on the Pennsylvania Department of Environmental Protection (PADEP) unconventional gas wastewater database.[2]

Two key factors affect the *demand* for produced water as blendstock for well completion. First, well completion activity follows the price of natural gas. In 2012,

[2] The database is available at www.paoilandgasreporting.state.pa.us/publicreports/Modules/DataExports/DataExports.aspx.

because of low natural gas prices, only about 540 horizontal gas wells were completed in the PA Marcellus, although 1,365 such wells were drilled. (Noncompleted wells are capped, ready to be completed and put into production when the market conditions are favorable.) Second, weather and ground conditions affect the rate of completions.

Disposal of Excess

When the supply of produced water exceeds the demand, the excess requires disposal. In Pennsylvania some of this wastewater was sent to publicly owned treatment works (POTWs) from 2007 through mid-2011, when, on behalf of the governor, the PADEP secretary asked that all exploration and production companies and drillers in the state voluntarily cease this practice. This request yielded 100 percent compliance.

Since 2011 produced water disposal in Pennsylvania has been solely by injection into Class II salt water disposal wells instead of POTWs (Rassenfoss 2011). However, the cost of transportation from Williamsport, PA, an area of intensive shale gas development, to Youngstown, OH—about 190 miles away—is about $12/barrel. In addition, there is controversy over a possible connection between deep-well injection and small earthquakes (Frohlich 2012). In light of these concerns, deep-well injection is viewed as less than ideal for produced water disposal in Pennsylvania. Another option, which has not yet been implemented on a commercial scale, is water and salt recovery.

Opportunities for Water and Salt Recovery

Excess produced water creates opportunities for water and salt recovery. Produced water with a high level of total dissolved solids (TDS),[3] such as the design case, requires the use of thermal methods, such as humidification-dehumidification, forward osmosis membrane distillation,[4] and mechanical vapor recompression.

One option is to recover only clean water. For the design case produced water composition, about 55 percent of the feed volume can be recovered (limited by the onset of NaCl precipitation); the remaining water leaves as a concentrate stream. Produced water is first pretreated to remove iron, manganese, suspended solids, and some of the magnesium to protect the thermal equipment from scaling. Disposal of the concentrate may be by deep-well injection, sale as well kill fluid, or dispatch to a crystallizer for further recovery.

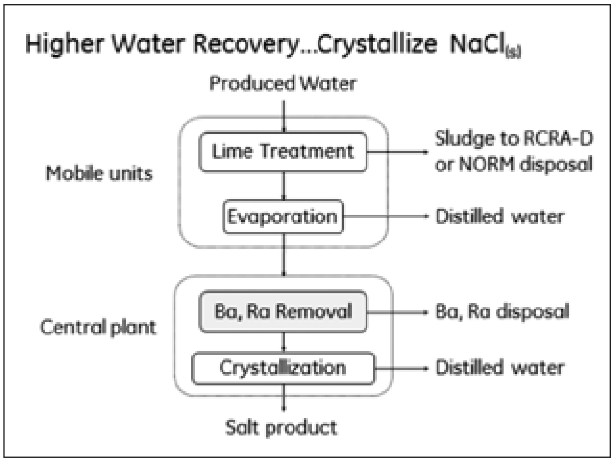


FIGURE 2 Evaporation/crystallization process for water and salt recovery. Ba = barium; NORM = naturally occurring radioactive material; Ra = radium; RCRA-D = subtitle D of the Resource Conservation and Recovery Act.

Alternatively, both clean water and a solid salt product may be recovered from the produced water. For the design case produced water composition, recovery of 90+ percent water and 90+ percent NaCl may be achieved through NaCl crystallization. Figure 2 shows one scheme for water and salt recovery. First, after appropriate pretreatment, mobile evaporators generate distilled water and concentrate. Next, in a central facility the concentrate is further treated to remove barium and radium to meet salt product specifications. Of seven methods considered for Ba and ^{226}Ra removal from produced water, sulfate coprecipitation was found to be the most cost effective (Silva et al. 2012). Finally, the concentrate is evaporated in a crystallizer to recover solid NaCl and distilled water. A small purge stream is disposed of by deep-well injection or sold as well kill fluid.

Disposal of Pretreatment Sludge

For a given produced water composition, a key economic and environmental concern is the activity concentration of ^{226}Ra in the sulfate pretreatment sludge vis-à-vis the permissible level for disposal in nonhazardous (RCRA-D) landfills (regulated under subtitle D of the Resource Conservation and Recovery Act). As there is no federal standard for these landfills, this regulatory

[3] For low-TDS produced waters (<35,000 mg/L TDS), reverse osmosis can be used for water recovery.

[4] Forward osmosis moves water across a membrane into concentrated draw solution, thus diluting the solution, from which water is then thermally recovered to reconcentrate the solution.

limit varies by state (Veil and Smith 1999). In Pennsylvania, based on guidance from PADEP,[5] a limited amount of sludge with up to about 140 pCi/gm radium is acceptable for disposal in RCRA-D landfills, as shown in Table 3. There are 50 RCRA-D disposal facilities in Pennsylvania, but no NORM disposal facilities[6]; other states, such as Texas, have facilities for NORM disposal. Table 3 shows the relative cost of nonhazardous waste disposal and NORM waste disposal.

The ^{226}Ra activity concentration in the sulfate sludge can be estimated by a material balance. Using 1.1 mole sulfate per mole barium, it is assumed that all Ba and ^{226}Ra in the raw produced water feed coprecipitate as $(Ba,Ra)SO_{4(s)}$, that all excess sulfate precipitates strontium as $SrSO_4$, and that the sludge is 30 wt percent solids. The results of this material balance are shown in Figure 3, where raw produced water Ba concentration is plotted on the x-axis and ^{226}Ra activity concentration on the y-axis. The lines that radiate from the origin are specific ^{226}Ra activity concentrations in the wet $(Ba,Ra)SO_4$ sludge resulting from combinations of Ba and ^{226}Ra concentrations in raw produced water. For example, the design case produced water yields sludge with just under 140 pCi ^{226}Ra per gram of wet sludge.

Sixteen PA Marcellus produced water sample compositions are superimposed on the plot in Figure 3. Several of these produced waters, particularly those with low Ba and high ^{226}Ra levels, would generate sulfate sludges that exceed the maximum acceptable ^{226}Ra activity for nonhazardous waste disposal in Pennsylvania. Others

TABLE 3 Disposal facility regulations and costs

Disposal facility	Maximum Ra activity, pCi/gm	Disposal cost, $/short ton
RCRA-D landfill	140[a] (Pennsylvania)	~$50[b]
NORM waste (oil and gas)[c]	n.a.	$550–$1,000

n.a. = not applicable; NORM = naturally occurring radioactive material; Ra = radium; RCRA-D = subtitle D of the Resource Conservation and Recovery Act
[a] Limited to 1% of landfill input.
[b] Information available at www.cleanenergyprojects.com/Landfill-Tipping-Fees-in-USA-2013.html.
[c] Vendor quotes including transportation cost from Williamsport, PA, to NORM waste disposal sites in Texas.

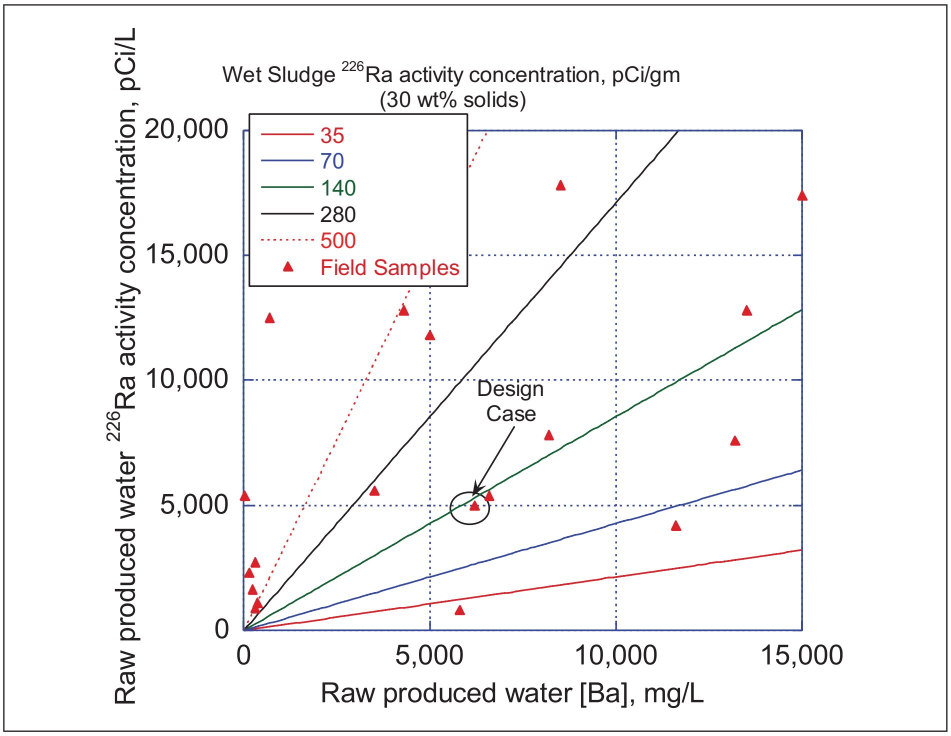


FIGURE 3 Map of produced water sulfate sludge radium activity concentration as a function of produced water barium (Ba) and radium (^{226}Ra) concentrations.

[5] The guidance from PADEP is given in terms of radiation dose rather than radium activity concentration. The inferred activity concentration limit is based on a conservative estimate that the radiation dose for a typical sludge rolloff container (in µRem/hr) is approximately equal to the average radium activity concentration for the contents of the container (in pCi/gm). A more precise correlation between dose and activity concentration should be applied if site-specific or updated regulatory guidance from PADEP is provided.

[6] PADEP is conducting a study on management of technologically enhanced NORM (TENORM) for produced water and treatment residuals (sludge). Information about the study is available at http://files.dep.state.pa.us/OilGas/BOGM/BOGMPortalFiles/RadiationProtection/TENORM-Study_SoW_04_03_2013_FINAL.pdf.

yield sulfate sludges that may be safely disposed of as nonhazardous waste.

This calculation shows that produced water NORM and Ba concentrations are key factors in the economic feasibility of water and salt recovery.

Conclusions

About 90 percent of produced water from the Pennsylvania Marcellus was reused in 2012, demonstrating that reuse is a valid option for management of shale gas–produced water. Often, only very simple treatment is needed for produced water reuse. However, as shale gas development in a given geographical region matures, the supply of produced water will exceed the demand for blendstock use in subsequent well completions. Because of the high TDS levels in Marcellus flowback and produced waters, thermal methods are required for water and salt recovery. Although implementation of water and salt recovery is still in its infancy, solutions exist today that are both technically and economically feasible.

Acknowledgments

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References

Considine TJ, Watson R, Blumsack S. 2010. The economic impacts of the Pennsylvania Marcellus Shale natural gas play: An update (May 24). Pennsylvania State University, Department of Energy and Mineral Engineering. Available at http://marcelluscoalition.org/wp-content/uploads/2010/05/PA-Marcellus-Updated-Economic-Impacts-5.24.10.3.pdf.

Frohlich C. 2012. Two-year survey comparing earthquake activity and injection-well locations in the Barnett Shale, Texas. Proceedings of the National Academy of Sciences 109(35):13934–13938.

Gaudlip T. 2010. Preliminary assessment of Marcellus water reuse. Presented at the Process-Affected Water Management Strategies Conference, March 17, Calgary, Alberta, Canada.

King G. 2012. Hydraulic fracturing 101: What every representative, environmentalist, regulator, reporter, investor, university researcher, neighbor, and engineer should know about estimating frac risk and improving frac performance in unconventional gas and oil wells. Society of Petroleum Engineers Paper SPE 152596.

Mantell M. 2011. Produced water reuse and recycling challenges and opportunities across major shale plays. Presented at EPA Hydraulic Fracturing Study Technical Workshop #4, March 29–30.

McCurdy R. 2011. Underground injection wells for produced water disposal. Proceedings of the Technical Workshops for the Hydraulic Fracturing Study: Water Resources Management, May. Available at www2.epa.gov/sites/production/files/documents/HF_Workshop_4_Proceedings_FINAL_508.pdf.

Minnich K. 2011. A water chemistry perspective on flowback reuse with several case studies. In: Proceedings of the Technical Workshops for the Hydraulic Fracturing Study: Water Resources Management. Washington: US Environmental Protection Agency.

Nicot JP, Reedy RC, Costley RA, Huang Y. 2012. Oil and Gas Water Use in Texas: Update to the 2011 Mining Water Use Report, Table 7. Prepared for the Texas Oil and Gas Association, Austin.

Rassenfoss S. 2011. From flowback to fracturing: Water recycling grows in the Marcellus Shale. Journal of Petroleum Technology 63:48–51.

Silva JM, Matis H, Kostedt W, Watkins V. 2011. NORM removal from hydrofracturing water. International Water Conference, paper IWC-11-07, Orlando, FL.

Silva JM, Matis H, Kostedt W, Watkins V. 2012. Shale gas produced water pretreatment for barium and radium removal. International Water Conference, paper IWC-12-56, San Antonio, TX.

Snoeyink V, Jenkins D. 1980. Water Chemistry. Hoboken, NJ: John Wiley & Sons.

Veil J, Smith K. 1999. NORM disposal options, costs vary. Oil & Gas Journal 97:37–43.

A sustained, concerted effort by those in industry, public health, regulatory agencies, and academia is needed to identify potential risks and reduce illness and fatalities in the oil and gas extraction industries.

Occupational Health and Safety Considerations in Oil and Gas Extraction Operations

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The onshore oil and gas industry has experienced rapid growth in upstream extraction production, in part due to the use of hydraulic fracturing (fracking) in unconventional wells. Although hydraulic fracturing is not a new process, its use has increased significantly in the past decade with the introduction of horizontal drilling and multistage fracking technologies. With the rise in production has come an escalation in risks of occupationally related injury, illness, and fatality. These risks are described together with some approaches to risk reduction and remediation.

Employment in the US Oil and Gas Extraction Industry

Employment in the US oil and gas extraction industry has grown dramatically in recent years. The Energy Information Agency reports that in 2012 the industry employed approximately 579,000 workers in drilling, extraction, and support activities, an increase of more than 162,000 jobs or 40 percent since 2007.[1] The North American Industry Classification System (codes 21111, 213111, 213112) characterizes these jobs as follows[2]:

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[1] "Oil and Gas Industry Employment Growing Much Faster Than Total Private Sector Employment." US Energy Information Agency, August 2013. Available at www.eia.gov/todayinenergy/detail.cfm?id=12451#.

[2] NAICS information is from the US Census Bureau, available at www.census.gov/cgi-bin/sssd/naics/naicsrch?chart=2012.

- drilling, completing, servicing, and equipping wells;
- operating separators, emulsion breakers, de-silting equipment, and field gathering lines for crude petroleum and natural gas; and
- performing other activities in preparing oil and gas up to the point of shipment from the producing property.

Occupational Injuries and Fatalities

The National Institute for Occupational Safety and Health (NIOSH), in an analysis of the Bureau of Labor Statistics (BLS) Census of Fatal Occupational Injuries, reported an annual occupational fatality rate of 27.5 per 100,000 workers in the oil and gas extraction industry from 2003 to 2009[3]—seven times higher than the rate for all US workers, which was 3.9 per 100,000 workers.[4] More than half (53 percent) of all fatalities among oil and gas workers were of those who had less than one year on the job (Hill 2012).

Correlating Factors

The industry's fatality rate correlates directly with the level of drilling activity, as measured by the number of active rotary rigs[3]: as the number of drilling and workover rigs increases, so does the fatality rate. The reported fatality rate controls for the number of workers in the industry, so changes in the rate are related to other factors, such as an increase in the number of inexperienced and inadequately trained workers and longer work hours (associated with worker fatigue) (Retzer et al. 2012a). Moreover, in times of high demand older rigs with fewer safety guards may be brought back into service as well as small companies that typically don't operate during a downturn.[3]

Oil and gas extraction industry fatality rates are further correlated with both the type (drilling, well servicing, and operation) and size of the establishment (small, medium, large).[3] NIOSH analysis of fatality rate by company type and size showed that workers employed by drilling companies had the highest fatality rate, followed by workers in well servicing companies, and then operators, irrespective of establishment size (Hill 2012).[5]

Small companies had the highest fatality rate for all three company types. There are several possible reasons for this correlation. In NIOSH's work with industry, discussions have indicated that small companies may not have health and safety staff, staff may have competing responsibilities, and health and safety programs may not be as well developed as at medium and large companies. In addition, small drilling contractors may lack the technologies (e.g., top drive, power tongs, pipe handling) that isolate workers from hazardous tasks, and small operators may have different safety expectations from those of large operators (Hill 2012).

Types of Injuries

The relative frequency of different types of fatalities in the US oil and gas extraction industry is shown in Table 1 (Hill 2012). Transportation incidents are the most frequent, followed by contact with objects or

TABLE 1 Fatal events for oil and gas extraction workers in the United States, 2003–2011

Type of injury event	Fatalities	% Total
Transportation incidents	371	39.7
Contact with objects/equipment	259	27.7
Fires and explosions	134	14.3
Exposure to harmful substances/ environments	88	9.4
Falls	65	7.0
Other[a]	18	1.9
Total	935	100.0

[a] Includes "Violence and other injuries by person or animal," "Overexertion and bodily reaction," and "Nonclassifiable."

Sources: Based on data from the Bureau of Labor Statistics Census of Fatal Occupational Injuries Charts, 1992–2012 (available at www.bls.gov/iif/oshwc/cfoi/cfch0011.pdf); Hill (2012); and personal correspondence with Ryan D. Hill, manager, NIOSH Oil and Gas Safety and Health Program, February 14, 2014.

[3] Information about Oil and Gas Extraction: Occupational Health and Safety Risks is available from NIOSH at www.cdc.gov/niosh/programs/oilgas/risks.html.

[4] Data from the BLS Census of Fatal Occupational Injuries Charts, 1992–2012, available at www.bls.gov/iif/oshwc/cfoi/cfch0011.pdf.

[5] Ryan D. Hill, manager, NIOSH Oil and Gas Safety and Health Program, personal correspondence, February 14, 2014.

equipment, fires and explosions, exposure to harmful substances/environments, and falls. The motor vehicle fatality rate for workers in the oil and gas industry subsector was more than eight times higher than that of private workers in all other industry sectors (Hill 2012). Fatigue associated with long hours (8- or 12-hour shifts for 7 or 14 days in a row) is believed to be a significant contributor to the motor vehicle crashes.[6]

In contrast to fatal injuries, most segments of the oil and gas extraction industry report a *lower* nonfatal injury rate than the average for private industry. For example, in 2010 the estimated annual rate of nonfatal work-related injuries for all job categories was 1.2 per 100 full-time workers, 1.9 for workers in support activities for oil and gas extraction, and 3.3 for drilling oil and gas wells.[3] During the same year the annual rate for all private industries was 3.5 nonfatal injuries per 100 full-time workers.[3] Whether due to underreporting or other recordkeeping issues, the reason for the lower reported injury rate for oil and gas extraction workers is not clear.

Accident Prevention Programs

To address the high fatality rate, safety training specific to the oil and gas industry has been developed by the Occupational Safety and Health Administration (OSHA)[7] and NIOSH.[8] In addition, some companies have initiated in-vehicle monitoring programs that record date, time of day, speed, acceleration, deceleration, and safety belt use. It is estimated that these programs can lead to a 50–93 percent reduction in motor vehicle crash rate (Retzer et al. 2012b).

Wyoming provides an example of a state-based accident prevention program. In June 2011 the Wyoming Oil and Gas Safety Alliance (www.wyomingsafety.org) and Wyoming OSHA entered into a formal collaboration to foster a safer workplace and healthier workers. One important measure is the Stop Work Authority, which establishes the *responsibility and obligation* of any individual to suspend a work task or group operation when one of the following occurs: the control of a health, safety, and/or environment risk is not clearly determined or understood, or a previously unforeseen hazard or risk is recognized and, if left uncorrected, may result in injury or damage.

Exposure to Toxic Agents

The second broad category of health risks in the oil and gas industry, after injury or fatality, involves acute and long-time exposures to toxic agents. NIOSH (2010) has created a program to assess exposure risks to oil and gas workers, with the following goals:

- identify processes and activities where chemical exposures could occur;
- characterize potential exposures to vapors, gases, particulates, and fumes; and
- recommend safe work practices and/or propose and evaluate exposure controls (e.g., engineering controls, substitution, personal protective equipment).

A number of specific agents have been evaluated—respirable crystalline silica, diesel particulates, hydrogen sulfide, volatile organic compounds (e.g., benzene), acid gases (HCl) and caustic compounds (NaOH), aldehydes used as biocides, heavy metals (e.g., lead), radioactive materials (e.g., uranium, thorium, radon), and noise. These agents are not unique to the oil and gas industry, and there is significant experience in the occupational health and safety field in understanding and reducing or eliminating their impacts on workers' health.

Benzene, for example, is a carcinogen that can cause aplastic anemia and leukemia, and exposure to it is regulated by OSHA standards. But the oil and gas extraction industry is exempted from the national benzene standard. Historically, OSHA has based the rationale for this exemption on data showing that "average worker exposures would be well below the action level" (OSHA 1995). There has been increasing concern, however, that the benzene levels may be higher than previously thought. NIOSH is involved in a study of volatile organic compound exposures in the oil and gas extraction industry.

Silica Exposure

Of all the agents listed above, silica is receiving the most attention in the oil and gas industry. A large quantity of silica sand is commonly used as a proppant to hold

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[6] Ryan D. Hill, manager, NIOSH Oil and Gas Safety and Health Program, personal correspondence, April 26, 2013.

[7] OSHA information about safety and health topics related to oil and gas extraction is available at https://www.osha.gov/SLTC/oilgaswelldrilling/index.html.

[8] NIOSH information about Oil and Gas Extraction Outputs: Products is available at www.cdc.gov/niosh/programs/oilgas/products.html.

FIGURE 1 Worker exposure to silica dust during sand transfer operations. Photo shows sand mover and transfer system. Reprinted from NIOSH/OSHA (2012).

open cracks and fissures during hydraulic fracturing. Exposure to respirable crystalline silica particles (less than 5 micrometers) occurs during blending and sand loading operations, sand truck refilling, and sand mover operations, all of which produce freshly fractured quartz (Figure 1; Esswein et al. 2013), which has been shown to have greater toxicity than aged quartz (Castranova et al. 1996; Shoemaker et al. 1995). Such exposure induces an inflammatory reaction in the lung and causes diseases such as silicosis (acute, accelerated, chronic) (Banks 2005) and chronic obstructive pulmonary disease (Möhner et al. 2013). Workers with silicosis also have a greater risk of tuberculosis.

The International Agency for Research on Cancer evaluated the carcinogenicity of respirable crystalline silica and concluded that inhaled quartz and cristobalite were carcinogenic in occupational settings (IARC 2012). Silica exposure has also been linked with autoimmune diseases (Miller et al. 2012) that are related to chronic inflammatory effects; these diseases include rheumatoid arthritis (Rosenman and Zhu 1995), scleroderma (Sluis-Cremer et al. 1985), systemic vasculitis (Gómez-Puerta et al. 2013), systemic lupus erythematosus (Brown et al. 1997), and chronic renal disease (Vupputuri et al. 2012).

Workplace exposure limits have been established to address the dangers of silica. The current OSHA permissible exposure limit (PEL) for respirable crystalline silica (quartz) is approximately equivalent to 100 $\mu g/m^3$ as an 8-hour time-weighted average (TWA),[9] but a more protective PEL is being proposed[10] in line with the NIOSH recommended exposure limit (REL) for respirable silica of 50 $\mu g/m^3$ (NIOSH 2002). The American Conference of Governmental Industrial Hygienists recommends the most protective threshold limit value (TLV), 25 $\mu g/m^3$ for a TWA exposure based on an 8-hour workday (ACGIH 2012).

However, research has shown that silica levels for oil and gas workers in and around dust generation points are above the recommended occupational exposure limits. In a recent study NIOSH collected 111 personal breathing zone (PBZ) samples from workers with 15 different job titles at 11 well sites in 5 states (Arkansas, Colorado, North Dakota, Pennsylvania, and Texas) under all conditions to evaluate worker exposures to respirable crystalline silica during fracking (Esswein et al. 2013). Of the 111 samples 83.8 percent exceeded the TLV, 68.5 percent exceeded the REL, and 51.4 percent exceeded the PEL for respirable silica. The jobs most at risk were sand mover operators and T-belt operators—their PBZ exposures exceeded the REL or PEL by a factor of 10 or more.

Prevention of Exposure to Silica: Hierarchy of Controls

Protection of workers who are exposed to silica during hydraulic fracturing operations will require a combination of engineering controls, product substitution where feasible, improved work practices, worker training, and proper protective equipment. Table 2 shows a hierarchy of controls recommended to eliminate or reduce exposure to silica (Esswein and Hill 2013).

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[9] OSHA regulations for occupational exposures to crystalline silica are available at https://www.osha.gov/dsg/topics/silicacrystalline/osha_standards_silica.html.

[10] OSHA's Proposed Rule on Occupational Exposure to Respirable Crystalline Silica (09/12/2013) is available in the Federal Register at https://www.federalregister.gov/articles/2013/09/12/2013-20997/occupational-exposure-to-respirable-crystalline-silica.

TABLE 2 Hierarchy of controls for reducing exposure to silica

Elimination	• Prevention through design (PtD) • Remote siting of operations (if feasible)
Substitution	• Use of man-made ceramic material or other alternative proppants instead of sand
Engineering controls	• Passive enclosures • Stilling (staging) curtains, skirting, shrouding • Minimized distance that sand falls • End caps on fill nozzles • Use of amended water for site dust control
Administrative controls	• Rotation of personnel • Limitations on worker time at dust sites
Personal protection	• Effective respiratory protection program • Signage • Effective hazard communication • Inclusion in job safety and health analysis • Periodic training • Medical monitoring

Elimination of the toxic agent is always the first and best approach. In this regard, proper engineering design of processes and equipment is key. Such design measures may involve incorporation of skirting, filters, and shrouds by retrofitting existing equipment (Esswein and Hill 2013).

Even better is building these protections into the original engineering design.[11] Some operators have substituted manufactured ceramics (Esswein et al. 2013; NIOSH/OSHA 2012) as the proppant instead of silica sand to reduce respirable crystalline silica exposure. Other means for reducing exposure involve strong administrative control over operations, such as limiting the number of workers and time spent in areas of high dust.

In addition, OSHA's Hazard Communication standard requires that employers provide training and information in a manner and language that each worker understands to ensure that informed workers engage in safe work practices.

[11] NIOSH provides online guidance on "prevention through design" (PtD) at www.cdc.gov/niosh/topics/ptd/.

Summary

Although the high fatality rate among oil and gas extraction workers has been noted for more than a decade, the rapid increase in the number of workers in the past five years and the expansion of the industry to a greater number of states has brought the issue to the forefront. Research findings showing that fatality rates are highest among small companies (those with fewer than 20 employees) and workers with less than one year of experience, and that transportation incidents are the most frequent fatal event type, have spurred efforts for improved safety.

Novel intervention programs are needed to reduce the fatality rate in the oil and gas extraction industries. Reducing the exposure of workers to silica and other chemical agents is a complex, multifaceted problem that can best be addressed through principles of prevention through design. Improved occupational health and safety surveillance will help to capture the effectiveness of injury and illness prevention interventions.

Overall, a sustained, concerted effort by those in industry, public health, regulatory agencies, and academia is needed to identify potential risks and significantly reduce illness and fatalities in the oil and gas extraction industries.

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References

ACGIH [American Conference of Governmental Industrial Hygienists]. 2012. TLVs and BEIs: Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices. Cincinnati.

Banks DE. 2005. Silicosis. In: Textbook of Clinical Occupational and Environmental Medicine, 2nd ed. Rosenstock L, Cullen MR, Brodkin CA, Redlich CA, eds. Philadelphia: Elsevier Saunders. pp. 380–392.

Brown LM, Gridley G, Olsen JH, Mellemkjaer L, Linet MS, Fraumeni JF Jr. 1997. Cancer risk and mortality patterns among silicotic men in Sweden and Denmark. Journal of Occupational and Environmental Medicine 39:633–638.

Castranova V, Pailes WH, Dalal NS, Miles PR, Bowman L, Vallyathan V, Pack D, Weber KC, Hubbs A, Schwegler-Berry D, Xiang J, Dey R, Blackford J, Ma JYC, Barger M, Shoemaker DA. 1996. Enhanced pulmonary response to the inhalation of freshly fractured silica as compared with aged dust exposure. Applied Occupational and Environmental Hygiene 11:937–941.

CDC [Centers for Disease Control and Prevention]. 2008. Fatalities among oil and gas extraction workers: United States, 2003–2006. Morbidity and Mortality Weekly Report 57:429–431.

Esswein E, Hill R. 2013. Keeping up with the oil and gas rush: How NIOSH seeks to improve worker safety and health in the US upstream oil and gas industry. The Synergist (June/July):24–27.

Esswein EJ, Breitenstein M, Snawder J, Kiefer M, Sieber K. 2013. Occupational exposures to respirable crystalline silica during hydraulic fracturing. Journal of Occupational and Environmental Hygiene 10:347–356.

Gómez-Puerta JA, Gedmintas L, Costenbader KH. 2013. The association between silica exposure and development of ANCA-associated vasculitis: Systematic review and meta-analysis. Autoimmunity Reviews 12:1129–1135.

Hill R. 2012. Improving safety and health in the oil and gas extraction industry through research and partnerships. Presentation at the MAP ERC Energy Summit, April 12, Denver.

IARC [International Agency for Research on Cancer]. 2012. Silica dust, crystalline, in the form of quartz or cristobalite. In: A Review of Human Carcinogens, Part C: Arsenic Fibers, Metals, and Dusts, pp. 355–405. IARC Working Group on the Evaluation of Carcinogenic Risks to Humans. Lyon, France. Available at http://monographs.iarc.fr/ENG/Monographs/vol100C/mono100C-14.pdf.

Miller FW, Alfredsson L, Costenbader KH, Kamen DL, Nelson LM, Norris JM, De Roos AJ. 2012. Epidemiology of environmental exposures and human autoimmune diseases: Findings from a National Institute of Environmental Health Sciences expert panel workshop. Journal of Autoimmunity 39:259–271.

Möhner M, Kersten N, Gellissen J. 2013. Chronic obstructive pulmonary disease and longitudinal changes in pulmonary function due to occupational exposure to respirable quartz. Occupational and Environmental Medicine 70:9–14.

NIOSH [National Institute for Occupational Safety and Health]. 2002. NIOSH Hazard Review: Health Effects of Occupational Exposure to Respirable Crystalline Silica. Available at www.cdc.gov/niosh/docs/2002-129/.

NIOSH. 2010. Fact sheet: NIOSH field effort to assess chemical exposure risks to gas and oil workers. DHHS (NIOSH) Publication No. 2010-130. Available at www.cdc.gov/niosh/docs/2010-130/.

NIOSH/OSHA. 2012. Hazard alert: Worker exposure to silica during hydraulic fracturing. DHHS (NIOSH) Publication No. 2012-166:1–7. Available at https://www.osha.gov/dts/hazardalerts/hydraulic_frac_hazard_alert.pdf.

OSHA [Occupational Safety and Health Administration]. 1995. Interpretation (archived), Standard Number 1910:1028. Washington: US Department of Labor. Available at https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=interpretations&p_id=22022.

Retzer KD, Hill RD, Conway GA. 2012a. Mortality statistics for the US upstream industry: An analysis of circumstances, trends, and recommendations. Protecting People and the Environment—Evolving Challenges: SPE/APPEA International Conference on Health, Safety, and Environment in Oil and Gas Exploration and Production, September 11–13, Perth, Australia. Richardson, TX: Society of Petroleum Engineers, Paper No. 141602.

Retzer K, Tate D, Hill R. 2012b. Implementing an in-vehicle monitoring program: A guide for the oil and gas extraction industry. Presentation at OSHA Oil and Gas Safety and Health Conference, December 4–5, Dallas.

Rosenman KD, Zhu Z. 1995. Pneumoconiosis and associated medical conditions. American Journal of Industrial Medicine 27:107–113.

Shoemaker DA, Pretty JR, Ramsey DM, McLaurin JL, Khan A, Teass AW, Castranova V, Pailes WH, Dalal NS, Miles PR, Bowman L, Leonard S, Shumaker J, Vallyathan V, Pack D. 1995. Particle activity and in vivo pulmonary response to freshly milled and aged alpha quartz. Scandinavian Journal of Work, Environment and Health 21:15–18.

Sluis-Cremer GK, Hessel PA, Hnizdo E, Churchill AR, Zeiss EA. 1985. Silica, silicosis and progressive systemic sclerosis. British Journal of Industrial Medicine 41:838–843.

Vupputuri S, Parks CG, Nylander-French LA, Owen-Smith A, Hogan SL, Sandler DP. 2012. Occupational silica exposure and chronic kidney disease. Renal Failure 34:40–46.

Economic development activities are defining social changes in municipalities where shale-related development occurs and require adequate public policies to address them.

Social Impacts of Shale Development on Municipalities

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The shale revolution has been studied primarily for its regional and national economic benefits, which are due to the spread of industries in the shale-related supply chain. There has been significantly less attention to local costs and benefits.

The pace of economic development activities and their impacts are defining social changes in counties and municipalities where shale-related development occurs and require adequate public policies to address them. This article addresses economic, physical, and social impacts in Ohio municipalities and townships where upstream and midstream industries have been expanding their Utica shale operations.

Phases of Shale Development

There are three major phases to shale exploration: development, production, and reclamation. The development phase—drilling and creating midstream infrastructure—involves building well pads, roads, bridges, pipelines, gas plants, storage facilities, and other related structures. This 4- to 8-week phase is construction- and labor-intensive (with as many as hundreds of workers depending on the necessary infrastructure), but expectations for massive involvement of the state's labor force in the construction phase are uncertain. Many construction crews consist of nonresidents who travel among sites, and may return to the same site numerous times, to perform very specific operations that require particular skills.

The production phase of development is significantly longer—an average well can commercially produce for about 10 years at the current level of technology. Labor involvement is low (e.g., a dozen workers per well per year), but may likelier include local labor. Well maintenance, environmental monitoring, and processing gas plant jobs in this phase require highly and moderately skilled labor and pay salaries that are extremely attractive compared to average wages in rural areas.

The moderately labor intensive reclamation phase is very short (1–2 weeks) and may or may not involve local labor.

Scope and Concentration of Shale Gas Activity in Ohio

Since 2010, when the development of Utica shale started in Ohio, numerous counties and townships have been affected by the construction of wells, roads, pipelines, and other midstream infrastructure—from 33 drilled horizontal wells in 2011 to 300 in 2012 and 600 by the end of 2013 (these numbers do not include permitted wells).

As of June 2013, 737 drilled and permitted wells were concentrated in 140 townships in 23 counties. For example, there are 280 permits issued to drill shale wells in Carroll County alone, where the reported 2012 population was 28,587—about 100 people per well drilled. There are 7 wells per 10 square miles in Carroll County, but this density is significantly higher in the 13 townships where the well development is occurring. In neighboring Harrison County, which has the second largest number of issued drilling permits, there are about 150 people per well, and every 20 square miles of landscape averages 5 wells.

The top 10 townships in Ohio (based on number of approved drilling permits), with a total population of about 12,000 people, are home to 301 permitted wells—more than 40 percent of all horizontally drilled wells in the state (Table 1). In Loudon, Lee, Seneca, and Stock townships the number of people per well is fewer than 30, bringing the state's average number of people per well to below 40.

The impacts of this scale and concentration of development are discussed in the following sections.

TABLE 1 Top townships by permitted well count in Ohio, 2013[a]

Township, County	Well count[b]	2010 population	People per well
Loudon, Carroll	73	1,009	14
Lee, Carroll	40	1,087	27
Washington, Carroll	30	1,239	41
Union, Carroll	28	977	35
East, Carroll	26	843	32
Perry, Carroll	24	996	42
Seneca, Noble	24	486	20
Stock, Harrison	21	478	23
Hanover, Butler	18	3,296	183
Augusta, Carroll	17	1,619	95

[a] Data from the Ohio Department of Natural Resources and US Census Bureau.

[b] Well count is based on permits issued for drilling the horizontal segment of a well; according to Ohio regulations, permits should be realized within two years from the issuing date.

Economic Impacts

Studies have projected employment growth, wealth creation, and an increase in Ohio's gross state product from development of the Utica shale (e.g., ACC 2013; Kleinhenz and Associates 2011); conservative estimates point to the support of about 40,000 jobs and $5.8 billion in output[1] in 2013 (e.g., Thomas et al. 2012). The Ohio Department of Jobs and Family Services reports that in the fourth quarter of 2012, employment in core shale-related industries increased by 17.7 percent (1,319 jobs) compared to the same quarter in 2011.[2] At the same time, employment in ancillary industries (e.g., freight truck delivery and environmental consulting) declined by 0.1 percent (77 jobs).[3]

[1] Equivalent of gross state product.

[2] Core and ancillary industries in this report were identified using multiple studies of the Marcellus shale development in Pennsylvania. *Core industries* are essential for oil and gas development, such as pipeline construction and well drilling. *Ancillary industries* provide essential supplies and services for core industries, such as freight trucking and environmental consulting.

[3] Data from Quarterly Economic Trends for Ohio Oil and Gas Industries, July 2013. Ohio Department of Jobs and Family Services. Available at http://ohiolmi.com/OhioShale/Ohio%20Shale%20Report%20July%202013.pdf.

There are conflicting statistics about the number of jobs created in counties that are home to drilling and midstream projects, but there is no doubt that these counties experienced a boost of economic activity—sales receipts for 2013's first quarter were 14 percent higher ($4.1 billion) compared to 2012's first quarter ($3.6 billion) (Hill and Kinahan 2013).

There are many acres of land under drilling leases owned by public and institutional entities, schools, governments, and private businesses. These property owners are paid lease bonuses for granting drilling rights to oil- and gas-producing companies and receive royalty payments as a percentage of production value if a well drilled on their property produces hydrocarbons.

Increased wealth in some of these counties has introduced challenges such as a growing demand for financial services, financial management, and family wealth planning for those who have become "rich overnight." In addition, anecdotal stories of charitable donations from those in core shale counties indicate philanthropic development in these communities, but there are few management resources to support and guide such efforts.

The drilling boom of Utica is predicted to extend over the next 10 years, and the associated wealth accumulation and increased spending may be expected over, minimally, the next 20 years.

Jobs

Some 400 workers are typically needed to construct and maintain a well for its lifetime. They have about 150 different occupations and work at different times during the well's three phases. The total number of hours worked by these individuals on a single well over the course of the year is the equivalent of 11.5 full-time jobs.[4] For counties and townships with a high density of wells, the impacts can be substantial and threaten to overwhelm existing infrastructure and resources.

In Louisiana, development of the Haynesville shale began in 2006 and by 2008 had led to a reported increase of shale-related employment of 32,742 jobs (Loren C. Scott & Associates 2009, p. 10). Also in 2008, Barnett (Texas) reported the distribution of employment triggered by shale development across many sectors: 28 percent of jobs in retail, 15 percent in food services, 10 percent in new construction, 6 percent in each of the following—the crude petroleum and natural gas industry, maintenance and repair, and health services—and 4 percent and 3 percent in business services and transportation, respectively (Perryman Group 2011, p. 128). These statistics suggest the job opportunities that may accompany the Utica shale development and what skills people should acquire to be hired locally.

Infrastructure Challenges

The dramatic rise in Ohio's shale gas well development has resulted in considerable job growth and industry expansion in the associated townships and municipalities. The movement of equipment and supplies involves extensive truck traffic over local roads and requires increased housing for workers; office, storage, and production space for businesses; and significant business and social services and infrastructure to support business operations and minimize social disruption for local citizens. Other infrastructure challenges affect housing and hospitality business development; water, sewer, and telecommunications; and electricity.

Utica shale development significantly affects rural communities, which are less economically and socially diversified, have limited governance capacity, and cannot easily absorb change.

Housing assessments, for example, should consider new construction that will be purchased and occupied after the boom. Establishing the correct affordability bracket of new housing will help to ensure a successful real estate market for years to come and reduce the construction of houses doomed to foreclosure.

Other infrastructure needs are linked to housing and hospitality business development; in Carroll County, for example, a dozen motels are under construction. The local natural gas company is expanding its pipeline web to serve the increased residential and manufacturing demand. Private markets can finance increased needs

[4] Data from the Penn State Marcellus Center for Outreach and Research. Available at www.marcellus.psu.edu; also see http://news.psu.edu/story/175878/2009/06/23/job-growth-expected-natural-gas-industry-development.

for water, sewer, and telecommunications, and electricity may be subsidized by the government in accordance with the Rural Electrification Act.

Construction and maintenance of roads in an area of shale development are challenging due to the associated heavy truck traffic. This is less of a concern in Ohio, however, as many rural roads lack hard surfaces and development companies often build improved roads during the major construction phase. Moreover, Ohio's Chesapeake Company uses a flexible pipeline water system, significantly decreasing the number of trucks on roads and thus reducing the wear and tear on roads and improving public safety.

The biggest complication is the cost of increased emergency, social, and community services and whether local budgets can fund them.

Social Services and Quality of Life

Shale development significantly affects predominantly rural communities with relatively low population density, little economic and social diversification, and limited local governance capacity. These communities cannot easily absorb change, and the development has been associated with challenges to social and family services, emergency response services, and law enforcement. Increased communication capacity, enhanced equipment and training, and, most importantly, additional individuals are needed to provide these services.

Statistical evidence of population growth in townships specifically due to increased economic activity in the Utica footprint is lacking, but there is certainly an in-migration of temporary labor, which strains the availability of rental property and other local resources (the size and duration of this surge are largely dependent on the economic pace of the shale development).

Small community infrastructures are ill equipped to handle shale development–related emergencies and the increase in crimes related to the influx of male workers in their 20s and 30s. Increased substance abuse, disorderly conduct, and warrants from other states due to the nomadic nature of temporary workers all require an increased police presence. But neighboring townships with populations of about 1,000 often share a sheriff and a volunteer fire response team.

Most temporary workers do not bring their families to the Utica region, but hosting communities should be ready for the associated challenges reported by townships in the Marcellus play, such as accommodating incoming children (e.g., in schools and day care) and hiring more staff for family and social services.

The biggest complication is the cost of increased emergency, social, and community services and whether the demand for these services occurs before local budgets can generate the income to fund them.

Local Perceptions

Although Marcellus shale development is significantly older than the Utica play, a 2011 survey in the Marcellus footprint showed 47 percent of Pennsylvanians supporting shale development, 19 percent opposing it, and a surprising 34 percent neither supporting nor opposing it and/or remaining undecided (Stedman et al. 2012). The same study indicates that 40 percent of respondents have limited or no knowledge of regulations, legal implications, drilling procedures, and employment opportunities. They knew only slightly more about economic, social, and environmental implications. Moreover, a higher number of survey respondents believed that their quality of life would decrease rather than increase as a consequence of the Marcellus development. They were greatly concerned about crime, affordable housing, road conditions, and environmental issues.

Conclusions

Utica shale development in Ohio raises many concerns that must be addressed to ensure successful and efficient development of both the state and local economies. In 2014 the critical phase of the state's midstream infrastructure development will determine the pace of shale development and set the stage for consequent social and economic impacts.

Shale development occurs largely in rural areas, where small municipalities and townships experience major social impacts. The rapid short-term influx of out-of-state workers has direct and significant consequences, such as changes in the community's culture and quality of life as well as cost-of-living and tax increases to cover the need for enhanced physical and social infrastructure.

An open community dialogue combined with state government assistance for educational and infrastructure needs can help capture the benefits and avoid a boom-to-bust cycle by establishing procedures and mechanisms for local control and sustainable long-term planning.

Most shale-related regulations are stipulated at the state government level, which is also where most tax benefits accrue (only a small share of increased state tax revenue comes to municipalities). Small communities often do not have the personnel and funding to respond to the challenges they face and lack land zoning regulations and appropriate strategies to address the changes associated with shale development.

Public policy changes are needed so that towns directly affected by shale development receive an appropriate share of economic benefits that currently accrue at the state and national levels. Appropriate policies can also promote local control and monitoring as well as training to help residents in affected communities acquire the skills needed to benefit from employment opportunities. State and municipal governments should support the creation of an inventory of major assets and resources, comprehensive plans including local regulations, and zoning and land development ordinances to bolster local control.

References

ACC [American Chemistry Council]. 2013. Shale Gas, Competitiveness, and New US Chemical Industry Investment: An Analysis Based on Announced Projects. Economics & Statistics Department, May. Washington.

Hill E, Kinahan K. 2013. Ohio Utica Shale Region Monitor. Published by Maxine Goodman Levin College of Urban Affairs, Cleveland State University, Ohio.

Kleinhenz and Associates. 2011. Ohio's Natural Gas and Crude Oil Exploration and Production Industry and the Emerging Utica Gas Formation: Economic Impact Study. Prepared for Ohio Oil and Gas Energy Education Program. Cleveland Heights, OH.

Loren C. Scott & Associates. 2009. The Economic Impact of the Haynesville Shale on the Louisiana Economy in 2008. Prepared for the Louisiana Department of Natural Resources. Baton Rouge. Available at http://dnr.louisiana.gov/assets/docs/mineral/haynesvilleshale/loren-scott-impact2008.pdf.

Perryman Group. 2011. A Decade of Drilling—The Impact of the Barnett Shale on Business Activity in the Surrounding Region and Texas: An Assessment of the First Decade of Extensive Development. Waco, Texas. Available at http://barnettprogress.com/media/BarnettShaleStudy11.pdf.

Stedman RC, Jacquet JB, Filteau MR, Willits FK, Brasier KJ, McLaughlin DK. 2012. Marcellus shale gas development and new boomtown research: Views of New York and Pennsylvania residents. Environmental Practice 14:382–393.

Thomas A, Lendel I, Hill E, Southgate D, Chase R. 2012. An analysis of the economic potential for shale formations in Ohio. Cleveland State University. Available at http://urban.csuohio.edu/publications/center/center_for_economic_development/Ec_Impact_Ohio_Utica_Shale_2012.pdf.

NAE News and Notes

NAE Newsmakers

William F. Banholzer, retired executive vice president and chief technology officer, Dow Chemical Company, and research professor, Chemical and Biological Engineering Department and Wisconsin Energy Institute at the University of Wisconsin-Madison, was the keynote speaker at the American Institute of Chemical Engineers (AIChE) 2014 Spring Meeting and Global Congress on Process Safety. In addition to setting the stage for the meeting, Dr. Banholzer received **AIChE's Government and Industry Leaders (AGILE) Award**, a recently established prize that celebrates the contributions of innovative executives who employ chemical engineers and who have made significant contributions to the chemical engineering profession. At the conclusion of his keynote lecture, Dr. Banholzer received the AGILE Award in recognition of his accomplishments at Dow, where he led the company's venture capital, new business development, and licensing activities.

Georges Belfort, institute professor, Howard P. Isermann Department of Chemical and Biological Engineering, Rensselaer Polytechnic Institute, has been awarded the **Alan S. Michaels Award for Innovation in Membrane Science and Technology** from the North American Membrane Society (NAMS). The award, given every three years "to recognize individuals who have made outstanding innovations and/or exceptional lifetime contributions to membrane science and technology," includes a $10,000 prize. Additionally, a special technical session has been organized in honor of Professor Belfort at the 2014 International Congress on Membrane and Membrane Processes meeting in July, in Suzhou, China.

On April 24 the Franklin Institute, which has honored the greatest minds in science, engineering, technology, and business for nearly 200 years, bestowed the 2014 **Bower Award for Business Leadership** on **William W. George**, professor of management practice, Harvard Business School. He received the award "for his visionary leadership of Medtronic Corporation, his promotion [of] and writings on corporate social responsibility and leadership, as well as his extraordinary philanthropic contributions to education and health care through the George Family Foundation."

The Association for Computing Machinery's Council on Women in Computing named **Susan T. Dumais**, distinguished scientist, Microsoft Research, as the **2014–2015 Athena Lecturer**. Dr. Dumais introduced novel algorithms and interfaces for interactive retrieval that have made it easier for people to find, use, and make sense of information. Her research, at the intersection of human-computer interaction and information retrieval, has broad applications for understanding and improving searching and browsing from the Internet to the desktop. The Athena Lecturer award celebrates women researchers who have made fundamental contributions to computer science and includes a $10,000 honorarium provided by Google Inc.

The International Mineral Processing Council (IMPC) and the Society for Mining, Metallurgy, and Exploration (SME) presented **Douglas W. Fuerstenau**, professor emeritus of mineral engineering, University of California, Berkeley, with an **IMPC/SME Special Award** for "outstanding contributions to the global mineral processing community through teaching, research, and professional service." The award was presented at the 2014 SME Annual Meeting in Salt Lake City. In addition, two special technical sessions at the meeting were designated **Fundamental and Applied Advances in Mineral Processing: A SME/IMPC Tribute to Professor Douglas W. Fuerstenau**. Fifteen invited papers were presented at these sessions. Also at the SME Annual Meeting, Professor Fuerstenau and **Dr. Pradip**, vice president, Tata Consultancy Services, Pune, India, were recipients of the **2014 SME Arthur F. Taggart Award** for their paper, "Design and development of novel flotation reagents for the beneficiation of Mountain Pass rare earth ore." The Taggart Award is given annually by SME for a paper or series of papers that represents a notable contribution to the science of mineral processing.

The American Association for Cancer Research (AACR) honored **Rakesh K. Jain**, Andrew

Werk Cook Professor of Tumor Biology (Radiation Oncology), Harvard Medical School and Massachusetts General Hospital, with the Eighth Annual **Princess Takamatsu Memorial Lectureship** at the AACR Annual Meeting on April 7, 2014. Dr. Jain was recognized for his pioneering work in tumor biology and his leadership in developing diverse international collaborations and training the next generation of scientists. The AACR Princess Takamatsu Memorial Lectureship is presented to a scientist whose novel and significant work had or may have a far-reaching impact on the detection, diagnosis, treatment, or prevention of cancer and who embodies the dedication of the princess to multinational collaborations. Her Imperial Highness Princess Kikuko Takamatsu was instrumental in promoting cancer research and encouraging cancer scientists.

Abraham E. Karem, president, Karem Aircraft Inc., was awarded the **Daniel Guggenheim Medal** on April 30 during the American Institute of Aeronautics and Astronautics (AIAA) Aerospace Spotlight Awards Gala in Washington, DC. Mr. Karem was honored "for a lifetime of innovative fixed and rotary wing unmanned vehicle designs." The Daniel Guggenheim Medal, established in 1929 and awarded jointly by the AIAA, the American Society of Mechanical Engineering (ASME), the American Helicopter Society (AHS) International, and the Society of Automotive Engineers (SAE) International, honors notable achievement in aeronautics.

The Association for Computing Machinery (ACM) named **Leslie Lamport**, principal researcher, Microsoft Research, to receive the **2013 ACM A.M. Turing Award** for imposing clear, well-defined coherence on the seemingly chaotic behavior of distributed computing systems, in which several autonomous computers communicate with each other by passing messages. He devised important algorithms and developed formal modeling and verification protocols that improve the quality of real distributed systems and have improved the correctness, performance, and reliability of computer systems. The ACM Turing Award, widely considered the "Nobel Prize in Computing," carries a $250,000 prize, with financial support provided by Intel Corporation and Google Inc. ACM President **Vint Cerf** noted that "as an applied mathematician, Leslie Lamport had an extraordinary sense of how to apply mathematical tools to important practical problems. By finding useful ways to write specifications and prove correctness of realistic algorithms, assuring a strong foundation for complex computing operations, he helped to move verification from an academic discipline to practical tool."

William F. Marcuson III, director emeritus, Geotechnical Laboratory, US Army Engineer Research and Development Center, US Army Corps of Engineers, was recently named a **Chi Epsilon National Honor Member**, an elite recognition based on distinguished accomplishments in the field of civil engineering and outstanding contributions to the object and purpose of Chi Epsilon. No more than two members may be elevated to National Honor Member during any biennium, and fewer than 70 leaders have been accorded the honor since Chi Epsilon's inception in 1922.

The International Society for Computational Biology (ISCB) announced **Eugene Myers**, director, Max-Planck Institute for Molecular Cell Biology and Genetics, as the winner of the **2014 Senior Scientist Accomplishment Award**. The award honors respected leaders in computational biology and bioinformatics for their significant contributions to these fields through research, education, and service. Dr. Myers is being honored for his outstanding contributions to the bioinformatics community, particularly for his work on sequence comparison algorithms, whole-genome shotgun sequencing methods, and recent endeavors in developing software and microscopic devices for bioimage informatics.

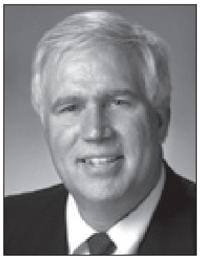
Harold A. Rosen, retired vice president, Hughes Aircraft Company, and consultant, received a lifetime achievement award from *Aviation Week & Space Technology* magazine on March 6 in recognition of his work that helped make possible global broadband communications. Dr. Rosen led the team that developed the groundbreaking Syncom satellite launched in July 1963; Syncom conclusively demonstrated the practicality of geosynchronous orbit.

The National Science Board (NSB) announced that **Richard A. Tapia**, University Professor and Maxfield-Oshman Professor in Engineering, Rice University, is the 2014 recipient of its **Vannevar Bush Award**. Dr. Tapia's research on computational optimization is highly regarded, as is his strong support of women and minorities in the sciences. "In addition to his distinguished contributions to mathematics, Richard Tapia has shown extraordinary leadership in increasing opportunities for underrepresented minorities in science and mathematics," said **Ruth David**, Chair of the NSB's Committee on Honorary Awards. "His long-term commitment and success sharing the excitement and relevance of mathematics and computer science with inner-city high school students and other members of the public is inspirational." The NSB presented Dr. Tapia with the Vannevar Bush Award on May 6 during the National Science Foundation/NSB Annual Awards Ceremony in Washington, DC.

Chair, Vice President and Councillors Elected

Charles O. Holliday, Jr.

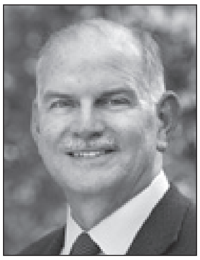
Corale L. Brierley



Richard A. Meserve

Frances S. Ligler

Arunava Majumdar

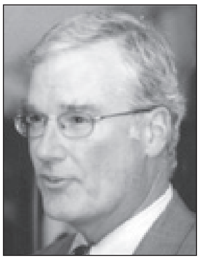


H. Vincent Poor

Wanda M. Austin

Maxine L. Savitz

Alice M. Agogino



Paul R. Gray

Julia M. Phillips

This spring NAE reelected the incumbent chair, elected a new vice president, reelected an incumbent councillor, and elected three new councillors. All terms begin July 1, 2014.

Reelected to a two-year term as NAE chair was **Charles O. Holliday, Jr.**, retired chairman of the board and chief executive officer of E.I. du Pont de Nemours and Co. Elected to a four-year term as NAE vice president was **Corale L. Brierley**, principal and founder of Brierley Consultancy LLC.

Richard A. Meserve, president of Carnegie Institution for Science, was reelected to a three-year term as councillor. Newly elected to three-year terms as councillors were **Frances S. Ligler**, Lampe Distinguished Professor of Biomedical Engineering in the joint department of biomedical engineering at the North Carolina State University College of Engineering and the University of North Carolina–Chapel Hill School of Medicine; Arunava Majumdar, vice president for energy at Google, Inc.; and **H. Vincent Poor**, dean of engineering and applied science and Michael Henry Strater University Professor at Princeton University. **Wanda M. Austin**, president and chief executive officer of the Aerospace Corporation, was elected by the NAE Council for a one-year term to fill the Council seat vacated by Corale Brierley.

On June 30, 2014, **Maxine L. Savitz** completed eight continuous years of service as vice president, the maximum allowed under the Academy's bylaws. Councillors **Alice M. Agogino**, Roscoe and Elizabeth Hughes Professor of Mechanical Engineering at the University of California at Berkeley; **Paul R. Gray**, executive vice chancellor and provost, emeritus, and professor in the department of electrical engineering and computer sciences at the University of California at Berkeley; and **Julia M. Phillips**, vice president and chief technology officer of Sandia National Laboratories, completed six continuous years of service, the maximum allowed under the Academy's bylaws. Drs. Savitz, Agogino, Gray, and Phillips were recognized in May for their distinguished service and other contributions to the NAE.

NAE Honors 2014 Draper Prize Winners

The NAE honors outstanding individuals for significant innovation, leadership, and advances in bioengineering. The 2014 Charles Stark Draper Prize for Engineering award winners were honored at a black-tie dinner on February 18 at the National Academy of Sciences in Washington, DC. The recipients accepted their awards before an audience of more than 140 guests, with NAE President **C. D. Mote, Jr.** and NAE Council Chair **Charles O. Holliday, Jr.** at the podium. Also assisting in the presentation was Frank Miller, chairman of the board of directors of Draper Laboratory and independent consultant and principal of the Scowcroft Group.

Charles Stark Draper Prize for Engineering

LEFT To right: Dr. C. D. Mote, Jr., Dr. John B. Goodenough, Mr. Yoshio Nishi, Dr. Rachid Yazami, Dr. Akira Yoshino, Mr. Charles O. Holliday, Jr., and Mr. Frank Miller.

John B. Goodenough, Yoshio Nishi, Rachid Yazami, and Akira Yoshino were awarded the 2014 Charles Stark Draper Prize for Engineering "for engineering the rechargeable lithium-ion battery that enables compact, lightweight mobile devices." The lithium-ion battery is used by millions of people around the world in cell phones, laptops, tablets, hearing aids, cameras, power tools, and many other compact, lightweight mobile devices.

In 1979 John B. Goodenough showed that the use of lithium cobalt oxide as the cathode of a lithium-ion rechargeable battery enabled a high density of stored energy with an anode other than metallic lithium. This discovery led to the development of carbon-rich materials that allow for the use of stable and manageable negative electrodes in lithium-ion batteries.

Shortly after Goodenough's breakthrough, Rachid Yazami began exploring graphite compounds in which lithium could be reversibly inserted between graphite layers. This provided an alternative to the lithium metal negative electrode. Yazami's lithium graphite is the most commonly used anode in commercial lithium-ion batteries today.

In 1985 Akira Yoshino produced a rechargeable lithium-ion battery prototype using a lithium cobalt oxide cathode and a carbon anode, eliminating metallic lithium. This design significantly improved the safety of the battery while also providing practical energy output at a reasonable price. Yoshino's work resulted in the first safety-tested, commercially acceptable lithium-ion battery.

While working at the Sony Corporation, Yoshio Nishi sought to make the lithium-ion battery a household item. After overseeing the development of the quality controls and safety characteristics necessary for mass producing the battery, Sony officially released the high-performance lithium-ion battery into the market under Nishi's supervision. The economic impact of the lithium-ion battery is now estimated at approximately $10 billion per year.

Acceptance Remarks by John B. Goodenough

John B. Goodenough

Tonight the National Academy of Engineering celebrates the role in society of materials engineering. We four are delighted and honored to participate in this celebration, and we are grateful to all those who have contributed—intellectually, financially, and as colleagues—to our presence here.

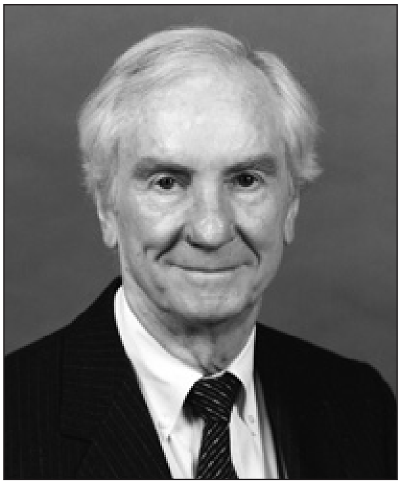
The Li-ion battery illustrates the complex process of innovation in materials engineering and the importance of both the support of the individual investigator and the availability of open international communication between scientists.

In the early 1970s there was a confluence of several events that led to the technology we are celebrating tonight: (1) the first energy crisis alerted the developed world to its vulnerability to dependence on imported oil, (2) the Three Mile Island incident helped to expose the limitations of nuclear energy, and (3) explorations by Jean Rouxel in France and Robert Schöllhorn in Germany of the chemistry of reversible Li intercalation into layered compounds, particularly sulfides, led to the suggestion of a rechargeable Li battery having TiS_2 as its cathode.

The Li/TiS_2 battery was abruptly abandoned after incendiary cell failures, failures that resulted from internal short circuits by dendrite growth from the metallic lithium anode to the cathode after repeated charge/discharge cycling. My contribution was to realize that an oxide cathode could allow a higher voltage and use of a Li-free anode in the fabrication of a discharged cell. This realization led to the development of the $LiCoO_2$ cathode in my laboratory at the University of Oxford. Quite independently, Rachid Yazami was exploring in Switzerland Li intercalation into graphite, a process he found did not result in dendrite formation providing the charging rate was not high enough to plate lithium on the surface of the graphite. In Japan, Akiro Yoshino, again quite independently, then understood he could assemble a rechargeable discharged cell with a Li-free graphite anode and a $LiCoO_2$ cathode to create a safe Li-ion battery. Yoshino Nishi of the Sony Corporation, Japan, used this battery to develop the first wireless telephone. With a marketable product, the wireless revolution was born.

The batteries of the wireless revolution do not have to compete with the energy stored in fossil fuels. Today, the engineering challenge is the development of electrochemical devices that will enable electric vehicles as well as the storage of electrical energy generated from wind and solar energy at a cost that is competitive with fossil fuels; this challenge is an urgent global priority for a sustainable modern society.

Peter O'Donnell, Jr. Gives $500,000 to Charles M. Vest President's Opportunity Fund



Peter O'Donnell, Jr.

In April, Peter O'Donnell, Jr., a long-time supporter of engineering, science, and math education, made a gift of $500,000 to the Charles M. Vest President's Opportunity Fund. The fund was established in 2012 by NAE members and friends of Dr. Vest, president of the NAE from 2007 to 2013, to honor his legacy and to support exploratory studies, new initiatives, and existing strategic programs at the Academy. Dr. Vest died in December 2013.

"Chuck was an extraordinary academic and engineer, impressive president of MIT, very able president of the National Academy of Engineering, and a man of excellent character. He is very much missed," Mr. O'Donnell said. "With this gift, I wanted to honor his important contributions to math, science, engineering education and policy."

Peter O'Donnell and his wife Edith founded the O'Donnell Foundation in Dallas in 1958. It has developed and funded model programs such as the Advanced Placement Incentive Program and the National Math and Science Initiative to strengthen engineering and science education in the 21st century as well as scientific research.

In addition, Mr. O'Donnell, together with former US Senator Kay Bailey Hutchison, was instrumental in founding the Academy of Medicine, Engineering, and Science of Texas (TAMEST).

Among his many national contributions, he served on the National Academies committee that produced *Rising Above the Gathering Storm*, funded the first three years of the NAE's Frontiers of Engineering Education Symposium, and supported the 2008 NSF-ICES conference on Simulation-based Science and Engineering in Washington, DC. The recipient of numerous awards and honors, O'Donnell was elected to the American Academy of Arts and Sciences and received a doctor of humane letters from Southern Methodist University.

"Peter O'Donnell's generous gift in tribute to former president Charles M. Vest will support NAE projects that will advance engineering solutions to many of society's greatest challenges," said NAE President C. D. Mote, Jr.

The Grainger Foundation Commits $3 Million for NAE Frontiers of Engineering Program

The National Academy of Engineering received a $3 million commitment from The Grainger Foundation in March to support the Frontiers of Engineering (FOE) symposia. It is the second $3 million commitment from the foundation in support of this program.

"We are pleased to continue our support for the Frontiers of Engineering symposia, which have a proven track record for establishing critical connections between outstanding young engineers around the world," said David Grainger, president and director of the foundation.

The funding also supports the foundation's Frontiers of Engineering Grants, which provide seed funding to US-based FOE participants to pursue projects stimulated by the symposia. Two grants of $30,000 were awarded to attendees of the 2013 US FOE Symposium.

Philip Feng, of Case Western Reserve University, and Tse Nga (Tina) Ng, at the Palo Alto Research Center, received a Grainger grant for "Integrating Atomically Thin Semiconducting Crystals with Flexible Electronics." The funds will support exploratory fundamental research on integrating an extremely thin layer of semiconducting crystals, specifically molybdenum disulfide (MoS_2), with state-of-the-art printed electronics on flexible substrates. This research could lead to innovative technologies and methods for integrating materials and may reveal new ways to incorporate novel 2D materials into functional devices.

The second Grainger grant was awarded to John Owens, of the University of California at Davis, and Tuhin Sahai, at the United Technologies Research Center, for "Parallel Matrix Factorization: Toward GPUs in the Data Center." The team will explore how to develop computational models that enable decision making from large amounts of data—for example, making movie recommendations to millions of subscribers based on their ratings of past viewings. The researchers will develop their algorithms on an emerging computer processor, the graphics processing unit (GPU), which takes a more parallel approach to solving computational problems.

"Thanks to the generous support of The Grainger Foundation, Frontiers of Engineering symposium participants have the opportunity to join together and take on innovative ideas in the pursuit of groundbreaking research," said NAE President C. D. Mote, Jr.

Established in 1995, the Frontiers of Engineering program includes a US symposium each year and a rotating schedule of bilateral meetings of engineers from the US and Germany, Japan, India, China, and the European Union. The 2½-day symposia provide an opportunity for attendees to network and learn about cutting-edge developments in fields other than their own. Attendees are competitively selected based on nominations by fellow engineers or organizations. Approximately 100 engineers, age 45 or younger, are invited to attend each year's US meeting, and 30 from each country attend the bilateral symposia. The meetings provide a window for US engineers to learn about developments at the forefront of technology in the global marketplace.

The Grainger Foundation, an independent, private foundation based in Lake Forest, Illinois, was established in 1949 by William W. Grainger, founder of W.W. Grainger Inc. The Frontiers of Engineering symposia also receive funding from government and corporate entities. For more information about the program, visit www.naefrontiers.org.

First Brazil-US Frontiers of Science and Engineering Held in Rio de Janeiro

BRAZIL-US Frontiers of Science and Engineering participants.

On March 17–19 the Brazil-US Frontiers of Science and Engineering Symposium was held at Rio Hotel Everest in Rio de Janeiro, Brazil. The symposium was noteworthy in two respects: (1) it was the first Frontiers meeting with Brazil and the first with a Latin American country, and (2) it was the first joint science and engineering Frontiers activity organized by NAE's Frontiers of Engineering and NAS' Kavli Frontiers of Science offices. The event was coorganized with the Brazilian Academy of Sciences and sponsored by the US National Science Foundation and, on the Brazilian side, CAPES (Coordination for the Improvement of Higher Education Personnel) and CNPq (National Council for Scientific and Technological Development). NAE member **Cristina Amon**, dean of applied science and engineering at the University of Toronto, and Alvaro Prata, secretary of the Department of Technological Development and Innovation in the Brazilian Ministry of Science, Technology, and Innovation, cochaired the organizing committee and the symposium.

The event brought together 60 engineers, ages 30–45, from US and Brazilian universities, companies, and government labs for a 2½-day meeting where leading-edge scientific and engineering research and technical work in four areas—Bioengineering and Public Health, Precision Nanotech, Biofuels, and Sustainable and Resilient Cities—were discussed.

The session on Bioengineering and Public Health focused on biomedical materials and devices for bridging the biotic-abiotic interface, or melding living systems with synthetic devices. This interaction raises interesting research challenges, the exploration of which can be mutually beneficial—new materials and devices can be used to unlock the mysteries of biology while expanding the impact of new biomedical technologies for improving human health. Talks covered the use of mathematical modeling and control of mechanical and biological systems with a focus on robotics for human rehabilitation, noninvasive and high-fidelity smart skin sensors to monitor physiology, microfluidics and micro-/nanotechnology platforms capable of testing cells and subcellular components with combinations of various stimuli, and developments and challenges of organ bioprinting using additive or 3D printing technologies.

Precision control is the key limitation to unlocking the full potential of nanotechnology. The Precision Nanotech session covered two key aspects of nanotechnology—the molecular perfection of graphene and the programmable fidelity of DNA nanostructures—that have led to new precision tools in nanotechnology to advance the next generation of applications. The first two speakers addressed the issue of carbon nanomaterials with talks on electronic and vibrational properties of carbon nanotubes and graphene and simulations of electronic transport in nanoscopic devices, particularly carbon-based systems such as graphene. The second set of speakers covered nanotechnology-based programmable nucleic acids, with presentations on the engineering of synthetic, nucleic acid–based nanostructures and resulting applications in biosensing, imaging, nanofabrication and tissue engineering, and a computational design framework, CanDo, that enables the in silico design and evaluation of functional DNA-based devices that enhance the design-build-test development cycle for next-generation nanoscale materials.

Recent research efforts in biofuels have focused on developing economically feasible processes for second-generation (cellulosic-based) biofuels and third-generation biofuels derived from CO_2. Significant challenges remain in bringing second- and third-generation biofuel technology to commercial-scale production. Speakers in the Biofuels session provided an overview of the field as well as recent developments in four areas: (1) improving the yield and productivity of feedstocks such as sugarcane and corn, (2) developing new conversion technologies that take into account the unique nature of chemical and thermochemical processes required for economical production of biofuels, (3) providing industrial-scale sustainable biofuels from a synthetic biology platform that converts plant sugars to a variety of molecules that can be used in a wide range of products, and (4) lifecycle analysis of biofuels.

The final session, Sustainable and Resilient Cities, brought together social science and engineering perspectives to address challenges specific to the urbanized world. Cities are hubs of technological and cultural innovation and policy responses to the world's most pressing issues, but they face air and water pollution, carbon emissions, and depletion of energy resources. Advances in renewable energy and information and communication technologies (ICT) make possible the vision of a digital city where innovative services and facilities meet the needs of an urban citizenry, businesses, and government. The first talk in this session described the competitive advantage of cities in fostering invention and innovation. This was followed by presentations on crowdsourcing and mobile and social techniques that facilitate city planning and engagement; the use of ICT to provide culturally sensitive information to citizens that supports community life; and methods that local governments have used to mainstream climate change planning across multiple constituencies.

In addition to the plenary sessions, there were lightning talks and poster sessions on the afternoons of the first and second days. These features served as both an icebreaker and an opportunity for all participants to share information about their research and technical work. Presentations by Prof. Sandoval Carneiro, manager for partnerships and funding in the Department of Technology and Innovation of VALE SA, and Dr. Guilherme Sales Soares de Azevedo Melo, director of engineering, exact sciences, and humanities at CNPq, provided overviews of science and technology in Brazil and initiatives to support international partnerships. Yaihara Fortis-Santiago, NSF AAAS Fellow, described NSF's international activities and programs that support collaborative work between Brazilian and US researchers.

Responses on the postsymposium survey indicate a strong desire for a second meeting that would be held in the United States. Potential sources of funding are being explored.

For more information about this or other Frontiers of Engineering or Kavli Frontiers of Science programs, contact Janet Hunziker (jhunziker@nae.edu) or Edward Patte (epatte@nas.edu), respectively.

NAE Regional Meetings

NAE Regional Meeting Held at the University of Virginia

With the merging of the physical and digital worlds in manufacturing, companies and universities are trying to address the challenges of what amounts to a new industrial revolution. To discuss these issues, an NAE regional symposium, "Challenges of Advanced Manufacturing," was held at the University of Virginia in the Rice Hall Auditorium on March 25.

James Aylor, dean of the U.Va. School of Engineering and Applied Science, opened the symposium by remarking that current issues and challenges in manufacturing provide opportunities to bring manufacturing back to the United States. "Advanced manufacturing, to accelerate and thrive, requires active participation of multiple communities," he said. As an example of U.Va.'s participation he cited the Engineering School and Curry School of Education's collaboration with Charlottesville and Albemarle County public schools to establish the first US Laboratory School for Advanced Manufacturing Technologies.

NAE President **C. D. Mote, Jr.**, explained that the NAE's regional meetings are similarly a means to bring together different groups, such as industry, students, and the community. On the topic of this symposium, he observed that "People think of assembly lines that are just making widgets when they think about manufacturing, but it is much broader." He invited participants "to think of manufacturing in a more holistic sense."

In the keynote address Joe Salvo, marketing communications manager for General Electric Co., said the world of connected machines will create an "Industrial Internet" that will support increased productivity, efficiency, and sustainability. And he mentioned that President Obama on February 25 announced two new public-private manufacturing innovation institutes to boost advanced manufacturing as well as the launch of the first of four new manufacturing innovation institute competitions.

He predicted that, by tapping into the "global knowledge base," state-of-the-art manufacturing equipment will totally change the manufacturing model and that there may one day be "some value of machine consciousness." If someone asked "how many friends does your computer have?" one might laugh, but, thinking of available computer automatic updates, he expected that this possibility may not be too far fetched.

"We are in the throes of the next industrial revolution powered by innovation. This is really the beginning of one age and the end of another," Salvo concluded.

The ensuing panel discussions on industrial and research challenges in advanced manufacturing featured industry experts and faculty members from U.Va. and Virginia Tech. The first speaker, Mike Fair, a project engineer at Siemens, pointed out that direct 3D printing of metal parts is quickly changing the industrial market. "Additive manufacturing is not just a new process, but an entire new philosophy," he said.

Next, Brian Warner, Rolls-Royce appointee to the Commonwealth Center for Advanced Manufacturing, argued that manufacturing research requires new technology and a balanced approach. He called for "[overcoming] the historic industry constraints by creating a new model of collaborative research."

David Dress, deputy, Space Technology Projects Office at NASA Langley Research Center, said NASA's focus on reducing the timeline for development and certification of innovative composite materials will help the US industry. The agency's goal, he said, is to reduce the typical 20 years from development to certification by 30 percent.

Rob Hogan, director, Structural Fab and Assembly, Newport News Shipbuilding, reported that inspectors use augmented reality glasses, which see real objects with computer-generated images overlaid, to find structural defects in seconds without having to test each support beam.

According to Peter Beling, associate professor of systems engineering at U.Va., the use of computers for human activity recognition and object tracking to understand actions in the workplace will help reduce risks and improve production times.

"Cyber security is a relatively new problem," said Jaime Camelio, associate professor in the Grado Department of Industrial and Systems Engineering at Virginia Tech. Citing the discovery in 2010 of the computer virus "Stuxnet," which almost ruined one-fifth of an Iranian nuclear centrifuge, he illustrated the very real possibility of a virus undermining product manufacturing.

Beth Opila, associate professor in the U.Va. Engineering School Department of Materials Science and Engineering, described the use of ceramic matrix composite (CMC) parts in aircraft turbo engines and the associated advantages and challenges that need to be addressed.

Additive manufacturing research opportunities have resulted in a manufacturing revolution, according to Chris Williams, assistant professor in the Departments of Mechanical Engineering and Engineering Education at Virginia Tech. He foresees future computers doing design and dynamic structural analysis.

The symposium was sponsored by the National Academy of Engineering, U.Va. School of Engineering and Applied Science, Virginia Tech College of Engineering, and Commonwealth Center for Advanced Manufacturing.

UC Davis College of Engineering and NAE Hold Meeting on Manufacturing

The UC Davis College of Engineering hosted an NAE regional meeting on April 1. Presentations and discussions focused on the challenges of transitioning innovative research from university laboratories to commercialization in the industrial and public sectors. The speakers included distinguished academics and entrepreneurs.

The "Symposium on Manufacturing" was opened by UC Davis College of Engineering Dean Enrique J. Lavernia, who said he was "quite thrilled to host the first-ever NAE regional meeting to be held at UC Davis." He also congratulated the attending Davis junior high and high school members of Citrus Circuits Team 1628, which won the Sacramento Regional FIRST Robotics competition a few days earlier.

NAE President C. D. Mote, Jr., took the stage and acknowledged the symposium's high attendance despite inclement weather and distances traveled by many of those present. He briefly discussed the NAE's history and importance to the United States and the world, and concluded with what could be considered his profession's mission statement: "Engineering creates solutions to serve the welfare of humanity and the needs of society."

UC Davis Chancellor Linda Katehi then championed the great strides made by the College of Engineering. "Our faculty have long been engaged in topics such as climate change and sustainability," she said, "long before those terms even were used to define such issues." She also shared an impressive metric: Among the College of Engineering's 202 faculty, 50 have won CAREER Awards, a phenomenal percentage for a comparatively young college that just celebrated its 50th anniversary.

The first presentation was by Curtis R. Carlson, president and CEO of SRI International. He argued that *now* is the best time ever for innovation, and presented statistics showing that the United States has the world's cheapest energy and an abundance of all resources, including potential talent. "But," he cautioned, "we're ignoring those in underprivileged environments.... We're growing a population of children with no skills to adapt and become part of today's society." Citing next-gen educational environments such as Stanford's d.school, Finland's Aalto University, and the Silicon Valley Girls' Middle School, he concluded by emphasizing the importance of education and human capital: "Great people want to make a difference, and we educators must create and maintain an environment to facilitate their efforts."

Biomedical engineer M. Allen Northrup, a UC Davis alumnus and principal of Northrup Consulting Group, spoke next. He briefly explained government's key role in funding valuable research that leads to innovation and commercialization, and cited the northern California biotech company Cepheid as an example. His remarks set the stage for David Persing, Cepheid's EVP and chief medical and technology officer, who focused on his company's most noteworthy success to date: a next-gen biochemical PCR (polymerase chain reaction) diagnostic device, GeneXpert, that enables speedy diagnoses of TB and other infectious diseases. Since 2011 the company has placed 1,800 GeneXpert systems in 98 of 145 eligible countries. *MIT Technology Review* has called it "the machine that will help end tuberculosis."

Persing explained that GeneXpert is a much faster means of determining whether a patient has contracted a contagious disease and has infected others. Traditional testing methods required three to six months to return results, by which time the patient—and others exposed—could have died. The Cepheid technology, he said, "has reduced diagnostic and analysis time to 90 minutes."

After a short break Cristina Davis, professor in the UC Davis Department of Mechanical and Aeronautical Engineering, discussed her research team's three key projects. The first focuses on micro-/nanosystems for biomedical breath monitoring, to provide (for example) asthma sufferers with a hand-held device to evaluate their condition in real time. The second involves a similar apparatus for enhancing precision agriculture by analyzing gas-phase compounds "exhaled" by plants under stress, with an eye toward the early detection of diseases such as huanglongbing (citrus greening). The third concerns health monitoring of marine mammals (as done by the US Navy's dolphin and sea lion fleet) by analyzing numerous biomarkers in their exhaled breath.

The final presentation was by Kyriacos A. Athanasiou, chair of the UC Davis Department of Biomedical Engineering (BME), who explained how a well-planned university ecosystem can facilitate the commercialization of BME technology. The sequence, he said, is straightforward: academic research yields new technology, which in turn leads to new startups. "But we don't just want to make *things*," he clarified. "We want to make *value*."

After quoting a 2013 *Forbes* magazine article that named biomedical engineering as the most valuable college major, Athanasiou presented several examples of the work done by his TEAM (Translating Engineering Advances to Medicine) students: the creation of replacement organs, such as ears, for human patients; the development of lifelike robotic hands for children who suffer from conditions such as amniotic band constriction; and the custom manufacturing of new bones and faces for pets that (for example) have developed cancer in their jaws. He concluded by recognizing the cofounders of several recent UC Davis startups—ViVita Technologies, StreamTex, TacSense, and AmberCycle—who were in the audience.

Lavernia returned to the dais to thank the speakers and attendees, and then invited everybody to a reception in the lobby.

The program, speakers' PowerPoint presentations, and speaker biographies are available at http://engineering.ucdavis.edu/events/national-academy-engineering-regional-meeting/.

NAE Regional Symposium at Princeton University Explores Intersection of Arts and Engineering

NAE Members (L to R) George Scherer, Jennifer Rexford, H. Vincent Poor.

The intersection of engineering and the arts provides fertile ground for both research and teaching, according to participants in an NAE regional meeting April 15 at Princeton University.

H. Vincent Poor, dean of the School of Engineering and Applied Science at Princeton, joined NAE president **C. D. Mote, Jr.**, in welcoming participants to the afternoon-long program. Poor noted that the so-called STEM fields—science, technology, engineering, and mathematics—are increasingly forging "an alliance with the creative and performing arts to enhance the work of both groups."

The symposium featured a range of Princeton faculty members from various engineering and arts disciplines. "Engineering and the arts are both creative fields, and so there is a natural and particularly productive connection between these two disciplines," Poor said.

The strength of those connections was evident in the presentation by Naomi Leonard, Edwin S. Wilsey Professor of Mechanical and Aerospace Engineering, and Susan Marshall, director of the university's Program in Dance. They described a joint project called Flock Logic, which combines Leonard's interest in the coordinated dynamics of networks of autonomous mobile agents such as birds, fish, or robotic vehicles, and Marshall's interest in creative avenues for expression and beauty in human movement.

Marshall and Leonard assembled groups of dancers and explored what happens when they were assigned simple rules of interaction, similar to those that seem to govern animal flocking (e.g., concerning cohesion and alignment with neighbors). The dancers produced intriguing and fluid patterns of movement that followed the rules and the interaction network in interesting ways.

For Marshall, an artistic goal was to "create tools for choreography by leveraging dynamics of multiagent systems with designed feedback and interaction." Leonard's engineering goal was to "develop insights and design principles for multiagent systems, such as human crowds, animal groups, and robotic networks, by examining what individual dancers do and what emerges at the group level."

As part of the Flock Logic project, experiments used video tracking technology to capture the trajectories and analyze the movements of dancers. In one such experiment, 13 dancers were instructed to stay arm's length from their two nearest neighbors as they moved around a large space. Leonard's research group used the trajectories and prescribed rules to estimate the interaction network at each frame of the video. From this they computed, for each dancer, a centrality measure, called "node status," which assigns a score from zero to one indicating how much attention that dancer was getting from the other dancers. The researchers found that the variation in node status among the dancers was significantly greater than that for a dynamic model of particles obeying forces analogous to the rules prescribed for the dancers. Indeed, two of the 13 dancers had node status almost two standard deviations above the mean, suggesting strong human bias.

That disparity in status and the possible connections to influence in networks begin to offer insights into group dynamics, Leonard said. The semicontrolled environment of dancers provides a unique laboratory that lies between animal behaviors, such as flocks of starlings, which present a lot of uncertainty, and computer simulations, which are highly prescribed.

In addition to the specific findings, Leonard said that an important message is that the collaborative process between an engineer and an artist was more synergistic than many might assume. A stereotype is that artists and engineers think very differently, but "we discovered that the process of creating something new was very similar." She said it starts with basic ideas and simple explorations, which advance to discarding ideas that are not working and proceeding with ones that are. The path often takes twists and turns but produces increasingly richer results and deeper understanding. Eventually a process of "reverse engineering" and active design or choreography is possible based on the resulting principles.

In a presentation on the "Art of Structural Engineering" Maria Garlock, associate professor of civil and environmental engineering, explored structures that both have strong aesthetic value and meet high standards of usefulness, performance, and economic value. She cited the work of architect Felix Candela, who designed elegant structures of surprisingly thin concrete shells, and Swiss bridge designer Robert Maillart.

Connections between technology and music were demonstrated by professor of music Dan Trueman. He cofounded the Princeton Laptop Orchestra, which performs compositions via laptop computers that interact with a variety of control devices and broadcast sound over hemispherical speakers. Trueman, an accomplished violinist, showed how alternative tunings of his instrument create entirely different tonal qualities and explained how such manipulations could be translated to technological devices for music making.

Princeton University Professor of Music Dan Trueman.

Professor of Computer Science Szymon Rusinkiewicz discussed collaborations using computer technology to reconstruct ancient art. He described a project that used 3D scanning and computer algorithms to find matches for shards of broken frescoes from the Greek island of Santorini.

"The talks were beautifully illustrated yet connected back to rigorous science," said **George Scherer**, William L. Knapp '47 Professor of Civil Engineering, who moderated the afternoon session with **Jennifer Rexford**, Gordon Y.S. Wu Professor in Engineering. He added that "there should be more of this kind of interaction because it's fruitful for both sides."

NAE at the USA Science and Engineering Festival

The NAE participated in the third USA Science and Engineering Festival on April 25–27 at the Washington Convention Center. The National Academies hosted "Decisiontown: Where Your Choices Matter," which was designed to showcase ways that citizens can use their knowledge of science, engineering, and health to make informed decisions for themselves and their communities. The NAE portion of Decisiontown was the "Town Arcade," which highlighted three of the Grand Challenges for Engineering: "Enhance Virtual Reality," "Engineer the Tools of Scientific Discovery," and "Reverse-Engineer the Brain." Arcade visitors used Microsoft's WorldWide Telescope virtual reality software to tour the "universes" of the brain and space both on a jumbo touch-screen and through motion sensor technology. The arcade also featured a gaming table where exhibit-goers played an MIT game, EyeWire, to map the brain; this crowd-sourcing tool allows people from all over the world to participate in real science.

NAE 50th Anniversary Video Contest

In celebration of its 50th anniversary, the NAE launched an "Engineering for You" (E4U) video contest to celebrate engineering and how its creations have served the welfare of humanity and the needs of society. Contest participants were asked to show how engineering, spanning the past 50 years and the next 50 years (1964 to 2064), has enhanced and will continue to enhance the quality of life for all. More information on the contest is available at www.e4uvideocontest.org.

A judges committee, chaired by **Robert Cook**, will select the top winners in the six categories of contestants as well as the winner of the $25,000 grand prize. The selection is a daunting task as over 600 entries were received by the deadline of March 31, 2014!

You too can be a judge for the People's Choice Award, which will be hosted on the National Academy of Engineering YouTube channel; this portion of the contest will run July 1–August 31, 2014. It will feature all the videos of the finalists, and the top vote getter will win a $5,000 prize.

All prize winners will be announced at the 2014 NAE Annual Meeting, September 27–29, 2014, in Washington, DC.

Calendar of Meetings and Events

April 28–29	Guiding Implementation of K–12 Engineering Committee Meeting
May 19–20	NRC-NAE Committee on Barriers and Opportunities in Completing 2- and 4-Year STEM Degrees Meeting Irvine, California
June 10–11	Committee on Engineering Technology Education Meeting
June 12	EngineerGirl 2014 Essay Contest Judges Committee Meeting
June 15	NAE-ASEE Workshop on Supporting Engineering & Engineering Technology 2-Year Transfer Students to 4-Year Institutions Indianapolis, Indiana
June 18–20	Committee on Women in Science, Engineering, and Medicine Meeting Irvine, California
June 26–27	Peace Tech Summit: Engineering and Technology for Enduring Peace
July 18	Frontiers of Engineering Education Advisory Committee Meeting Chicago, Illinois
June 30–July 2	Guiding Implementation of K–12 Engineering Committee Meeting
July 31–August 1	Committee on Engineering Education Workforce Continuum Meeting
August 2–4	NAE Council Meeting Woods Hole, Massachusetts
August 11–13	Guiding Implementation of K–12 Engineering Committee Workshop
September 10–12	Committee on Engineering Technology Education Meeting
September 11–13	US Frontiers of Engineering Irvine, California
September 26–27	NAE Council Meeting
September 27	NAE Peer Committee Meetings
September 28–29	NAE Annual Meeting

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

In Memoriam

In commemoration of the passing of NAE President Charles M. Vest, we invite readers to watch a video of the celebration of his life, held on February 20, 2014, and to read the PDF booklet of tributes based on that occasion, both featured on the NAE website (www.nae.edu).

RICHARD H. BATTIN, 88, retired senior lecturer, Massachusetts Institute of Technology, died on February 8, 2014. Dr. Battin was elected to the NAE in 1974 for contributions to the technology for control, navigation, and guidance for Apollo missions.

ARTHUR E. BERGLES, 78, Clark and Crossan Professor, Emeritus, Rensselaer Polytechnic Institute, died on March 17, 2014. Dr. Bergles was elected to the NAE in 1992 for seminal contributions and outstanding service and leadership in the field of heat transfer.

HOWARD BRENNER, 84, Willard H. Dow Professor of Chemical Engineering, Emeritus, Massachusetts Institute of Technology, died on February 17, 2014. Professor Brenner was elected to the NAE in 1980 for contributions in quantitatively modeling physicochemical transport processes in multiphase systems.

THOMAS P. HUGHES, 90, Mellon Professor Emeritus, University of Pennsylvania and Distinguished Visiting Professor, Massachusetts Institute of Technology, died on February 3, 2014. Dr. Hughes was elected to the NAE in 2003 for contributions to, and the effective dissemination of, the history of technology.

ALLEN E. PUCKETT, 94, chairman emeritus, Hughes Aircraft Company, died on March 31, 2014. Dr. Puckett was elected to the NAE in 1965 for outstanding contributions to aerodynamics and guided missile engineering.

MARK K. SMITH, 86, former vice president, Texas Instruments Inc., died on February 20, 2014. Dr. Smith was elected to the NAE in 1967 for development of seismic data processing.

GARETH THOMAS, 81, professor emeritus, University of California, Berkeley, died on February 7, 2014. Professor Thomas was elected to the NAE in 1982 for pioneering work in the application of transmission-electron microscopy to materials science and engineering.

ALEJANDRO ZAFFARONI, 91, founder, Alexza Pharmaceuticals, Inc., died on March 1, 2014. Dr. Zaffaroni was elected to the NAE in 1997 for contributions to human health care through creating and forging collaborations between the scientific and engineering disciplines.

Publications of Interest

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

The Importance of Engineering Talent to the Prosperity and Security of the Nation: Summary of a Forum. The quality of engineering in the United States will only be as good as the quality of the engineers doing it. Given the crucial importance of engineering to US prosperity, security, health, and well-being, the recruitment and retention of talented young people into engineering should be top national priorities. But only 4.4 percent of the undergraduate degrees awarded by colleges and universities in the United States are in engineering, compared with 13 percent in key European countries and 23 percent in key Asian countries. In the past the United States drew international engineering graduate students and professionals, but as other countries provide increasingly attractive opportunities for engineers, with excellent salaries, facilities, and economic growth potential, the United States can no longer assume that the best engineering talent in the world will want to come to this country. This report summarizes a forum at the NAE 2013 Annual Meeting at which speakers discussed opportunities and challenges of fostering and using engineering talent, and suggested recruitment and retention strategies.

NAE members on the panel were **William F. Banholzer**, retired executive vice president and CTO, The Dow Chemical Company, and research professor, Chemical and Biological Engineering Department, University of Wisconsin-Madison; **Alec N. Broers**, House of Lords, Westminster, United Kingdom; **John A. Montgomery**, director of research, US Naval Research Laboratory; and **Subra Suresh**, president, Carnegie Mellon University. Paper, $33.00.

Livable Cities of the Future: Proceedings of a Symposium Honoring the Legacy of George Bugliarello. With half the world's population living in cities, urban sustainability—encompassing security, economics, environment and resources, health, and quality of life—is of ever greater importance. George Bugliarello was a pioneer and champion of urban sustainability, and to honor his legacy a symposium on Livable Cities of the Future was hosted by the Polytechnic Institute of New York University in October 2012. More than 200 engineers, civic leaders, educators, and futurists gathered to discuss the manifestation of his vision in innovative urban planning. Participants heard from private and public service operators, infrastructure agencies, and the academic community; elected officials and other stakeholders in urban and other sectors examined issues critical to resilient and sustainable cities, such as energy, water supply and treatment, public health, security infrastructure, transportation, telecommunications, and environmental protection. The symposium presentations are summarized in this report.

NAE members of the symposium steering committee were **Thomas F. Budinger**, professor of the Graduate School, University of California, Berkeley, E.O. Lawrence Berkeley National Laboratory; **Lance A. Davis**, NAE executive officer; **Ivan T. Frisch**, retired executive vice president and provost, Polytechnic University, and Presidential Fellow, Polytechnic Institute of NYU; **Paul M. Horn**, Distinguished Industry Professor, NYU-Poly Department of Technology Management and Innovation, Distinguished Scientist in Residence and Senior Vice Provost for Research, New York University; **Thomas D. O'Rourke**, Thomas R. Briggs Professor of Engineering, Cornell University; **Katepalli R. Sreenivasan**, president and University Professor of Physics, Polytechnic Institute of NYU; **Charles M. Vest**, NAE president and president emeritus, Massachusetts Institute of Technology; and **Wm. A. Wulf**, NAE president emeritus and AT&T Professor of Computer Science and University Professor Emeritus, University of Virginia. Paper, $45.00.

Laser Radar: Progress and Opportunities in Active Electro-Optical Sensing. The range of technologies with the potential to threaten the security of US military forces has grown with developments in explosive materials, sensors, control systems, robotics, satellite systems, and computing power, to name just a few. Such technologies improve the capabilities not only of US military forces but also of potential adversaries. Passive and active electro-optical (EO) sensing technologies are prime examples. This report considers the potential of active EO technologies to create surprise; i.e., systems that use a source of visible or infrared light to interrogate a target in combination with sensitive detectors and processors to analyze the returned light. The report evaluates the physical limits to active EO sensor technologies with potential military utility; identifies key technologies that may help overcome impediments within 5 to 10 years; considers the pros and cons of implementing each existing or emerging technology; and evaluates the potential uses of active EO sensing technologies (e.g., 3D mapping and multidiscriminate laser radar).

NAE members on the study committee were **Elsa M. Garmire**, Sydney E. Junkins Professor of Engineering, Dartmouth College; **Peter F. Moulton**, principal research scientist, Q-Peak Incorporated; and **Eli Yablonovitch**, professor of electrical engineering and computer sciences, University of California, Berkeley. Paper, $62.00.

Stem Integration in K–12 Education: Status, Prospects, and an Agenda for Research. Leaders in business, government, and academia assert that education in the STEM subjects (science, technology, engineering, and mathematics) is vital not only to US innovation capacity but also to successful employment, whether or not in the STEM fields. K–12 STEM education, including standards and assessments, has tended to focus on the individual subjects, most often science and mathematics; the *T* and *E* have received relatively little attention. Recent reform efforts, such as the Next Generation Science Standards (NGSS), are stressing STEM connections (in the case of NGSS, between science and engineering). This report examines current efforts to connect the STEM disciplines in K–12 education. It identifies and characterizes approaches to integrated STEM education, in both formal and after- and out-of-school settings, reviews evidence for the impact of integrated approaches on student outcomes, and proposes priority research questions to advance understanding of integrated STEM education. The report presents a framework that supports a common perspective and vocabulary for researchers, practitioners, and others to identify, discuss, and investigate specific integrated STEM initiatives in the US K–12 education system, and it offers recommendations for designers of integrated STEM experiences, assessment developers, and researchers to design and document effective integrated STEM education.

NAE member **Linda M. Abriola**, Dean of Engineering, Tufts University, was a member of the study committee. Paper, $47.00.

Review of Department of Defense Test Protocols for Combat Helmets. Combat helmets have evolved considerably from those used in World War I to the current advanced design. One of the key advances was the development of aramid fibers in the 1960s, which led to today's Kevlar-based helmets. The Department of Defense continues to invest in research to improve helmet performance through better design and materials as well as better manufacturing processes. At the request of Congress, this report evaluates the adequacy of the advanced combat helmet test protocol for both first article testing and lot acceptance testing, including the use of the metrics of probability of no penetration and the upper tolerance limit (to evaluate backface deformation). The report also assesses the appropriate use of statistical techniques in gathering data, procedures for the conduct of additional analysis of penetration and backface deformation data, and scope of characterization testing relative to the benefit of the information obtained.

NAE member **Thomas F. Budinger**, professor, Graduate School, University of California, Berkeley, E.O. Lawrence Berkeley National Laboratory, was a member of the study committee. Paper, $54.00.

2013–2014 Assessment of the Army Research Laboratory: Interim Report. The NRC Army Research Laboratory (ARL) Technical Assessment Board provides biennial assessments of the scientific and technical quality of ARL's research, development, and analysis programs, focusing on ballistics sciences, human sciences, information sciences, materials sciences, and mechanical sciences. This interim report, summarizing the findings for the first year of this biennial assessment, presents the board's review of the following in each area: terminal ballistics (ballistic sciences); translational neuroscience and soldier simulation and training technology (human sciences); autonomous systems (information sciences, mechanical sciences); and energy materials and devices, photonic materials and devices, and biomaterials (materials sciences). The final report will incorporate the findings of both this report and the second year of the review, which will involve examination of additional elements.

NAE members on the study committee were **R. Byron Pipes** (chair), John L. Bray Distinguished Professor of Engineering, Purdue University, and **Jennie S. Hwang**, CEO, H-Technologies Group, and board trustee and Distinguished Adjunct Professor, Case Western Reserve University. Paper, $35.00.

Pathways to Urban Sustainability: Perspective from Portland and the Pacific Northwest: Summary of a Workshop. A workshop was convened in May 2013 to examine issues relating to sustainability and human-environment interactions in the Portland, Oregon, metropolitan region. (This was the last of three place-based urban sustainability workshops; the other two focused on Atlanta and Houston.) Topics included the role of land-use restrictions on development, transportation innovations, and economic and social challenges. Local, state, and federal officials, academics, and key stakeholders gathered to examine how challenges due to continued growth in the regions can be addressed in the context of sustainability. Among the elements contributing to Portland's success are strong public-private partnerships, a culture of planning, and a willingness to implement diverse ideas generated by federal, state, and local agencies, academics, and the private sector. This report highlights policy innovations and lessons that are potentially transferable elsewhere; focuses on ways to leverage local success through partnerships with state and federal agencies, companies, and nongovernment organizations; examines academic and corporate scientific and engineering research that could help cities become more sustainable; and considers how resource-constrained cities can become agents for broader societal goals not directly linked to their operational mandates, such as climate change mitigation, energy independence, and improvement in human health, particularly in low-income communities.

NAE member **Glen T. Daigger**, senior vice president and chief technology officer, CH2M Hill, was a member of the study committee. Paper, $42.00.

Undergraduate Chemistry Education: A Workshop Summary. The NRC Chemical Sciences Roundtable held a workshop to explore the current state of undergraduate chemistry education and to promote the transfer of lessons learned from the education research community to faculty with expertise in chemistry rather than in education. Participants from academia, industry, and funding organizations explored drivers of change in science, technology, engineering, and mathematics education; innovations in chemistry education; and challenges and opportunities in chemistry education reform. This report presents discussions of large-scale innovations that are transferable, widely applicable, and/or proven, with specific consideration of drivers and metrics of change, barriers to implementation, and examples of innovation in the classroom.

NAE member **Donna G. Blackmond**, professor of chemistry, Scripps Research Institute, was a member of the roundtable. Paper, $47.00.

Developing a 21st Century Global Library for Mathematics Research. Today's information technologies and machine learning tools provide an opportunity to further organize and enhance discoverability of the mathematics literature, with the potential to significantly facilitate mathematics research and learning and make information about the literature easier to express, encode, and explore. Many of the tools necessary to make this information system a reality will require community input paired with machine learning, where mathematicians' expertise can fill the gaps of automatization. The report proposes the establishment of an organization; the development of platforms, tools, and services; the deployment of an applied research program to complement the development work; and the mobilization and coordination of the mathematical community to take the first steps toward these capabilities. It recommends building on the extensive work done under the rubric of the World Digital Mathematical Library as well as many other community initiatives. A combination of machine learning methods and community-based editorial effort can make a significantly greater portion of the information and knowledge in the global mathematical corpus available to researchers through a central organizational entity, referred to in the report as the Digital Mathematics Library.

NAE member **Michael Lesk**, professor, Rutgers, The State University of New Jersey, was a member of the study committee. Paper, $43.00.

Emerging and Readily Available Technologies and National Security: A Framework for Addressing Ethical, Legal, and Societal Issues. An NRC-NAE study considered ethical, legal, and societal issues relating to research on, development of, and use of rapidly changing technologies with low barriers of entry that have potential military application (e.g., information technologies, synthetic biology, and nanotechnology) as well as ethical issues associated with robotics and autonomous systems, prosthetics and human enhancement, and cyber weapons. These technologies are characterized by readily available knowledge access, rapid technological advances, the blurring of lines between basic and applied research, and a high uncertainty about their future evolution and applications. This report addresses the ethics of using autonomous weapons that may be available in the future; the propriety of enhancing soldiers' physical or cognitive capabilities with drugs, implants, or prosthetics; and what limits, if any, should be placed on the nature and extent of economic damage that cyber weapons can cause. The report explores three areas with respect to emerging and rapidly available technologies: the conduct of research; research applications; and unanticipated, unforeseen, or inadvertent ethical, legal, and societal issues. A framework is provided for policymakers, institutions, and researchers to use in thinking about issues associated with these technologies of military relevance.

NAE members on the study committee were **William F. Ballhaus Jr.**, retired president and CEO, The Aerospace Corporation; **Jean-Lou A. Chameau**, president, King Abdullah University of Science and Technology; and **Alfred Z. Spector**, vice president, Research and Special Initiatives, Google Inc. Paper, $63.00.

Harvesting the Fruits of Inquiry: How Materials Discoveries Improve Our Lives. Condensed matter and materials research has played a key role in meeting US needs in areas such as energy, health, and climate change. This report highlights some of the societal benefits from research in this field, with examples that illustrate how such research has contributed directly to efforts to provide sustainable energy, meet health needs, and address climate change issues. Written in an accessible style, the report will be of interest to academia, government agencies, and Congress.

NAE member **Stuart S.P. Parkin**, IBM Fellow, manager, Magnetoelectronics, IBM Almaden Research Center, was a member of the study committee. Free PDF.

The Arc of the Academic Research Career: Issues and Implications for US Science and Engineering Leadership: Summary of a Workshop. America's research universities have undergone striking changes in recent decades, as have many aspects of the society that surrounds them, and these changes have important implications for faculty. Gender roles, family life, demographic makeup, and the economic stability of higher education all have shifted dramatically over the past generation, and current trends in technology, funding, and demographics suggest that such changes will continue. Yet the formal structure of the professorial career remains essentially unchanged. Developed in the mid-19th and early 20th centuries to suit circumstances quite different from today's (and based on even earlier traditions), this customary career path is now a source of strain for both the individuals pursuing it and the institutions where they work. At a workshop to examine major points of strain in academic research careers from the points of view of both the faculty and the institutions, experts from a variety of disciplines and institutions discussed practices and strategies already in use and identified issues not yet effectively addressed. This report conveys the workshop discussions and the challenges universities face—from nurturing the talent of future faculty members to managing their progress throughout their careers to finding the best use of their skills as their work winds down.

NAE members on the study committee were **Linda M. Abriola**, dean of engineering, Tufts University; **Paul Citron**, retired vice president, Technology Policy and Academic Relations, Medtronic Inc.; **David E. Daniel**, president, University of Texas at Dallas; **Gordon R. England**, president, E6 Partners LLC; and **Percy A. Pierre**, professor, Department of Electrical and Computer Engineering, Michigan State University. Paper, $40.00.

Development of Unconventional Hydrocarbon Resources in the Appalachian Basin: Workshop Summary. An NRC workshop was convened to examine the geology and unconventional hydrocarbon resources of the Appalachian Basin (the Marcellus, Utica, and Devonian shales), technical methods for producing these hydrocarbons and disposing of wastewater, the potential effects of production on the environment, relevant policies and regulations, and priorities for future scientific and engineering research. Experts in geosciences and engineering examined geoscientific aspects of hydrocarbon development (natural gas, oil, and natural gas liquids). A growing fraction of the oil and gas produced in the United States comes from geographically extensive accumulations of hydrocarbons in low-permeability rock with diffuse boundaries and no obvious traps or hydrocarbon-water contacts. This report focuses on the main hydrocarbon-bearing geologic formations in and around the Appalachian Basin and their estimated resources, current production levels, and projected output. The report examines potential effects on (1) surface water and groundwater quality and quantity and (2) landscapes and other environmental systems, and reviews technical and engineering processes for exploration and production.

NAE member **George M. Hornberger**, director, Vanderbilt Institute for Energy and Environment, and Distinguished University Professor, Vanderbilt University, chaired the study committee. Paper, $36.00.

Framing Surface Transportation Research for the Nation's Future: TRB Special Report 313. This report describes opportunities for improving the effectiveness of US expenditures on surface transportation research by building on lessons learned from strategic approaches in other countries and in US nontransportation sectors. Despite major progress in US transportation systems and services, particularly since the 1950s and 1960s, further improvements are needed if the nation is to continue competing effectively in the global marketplace and enhancing inhabitants' quality of life. Research is expected to play a major role in addressing the challenges facing US surface transportation. The committee that produced this report urges the timely development of a new national research framework that engages the public, private, academic, and nonprofit sectors and draws on the nation's research capacity in academia, industry, and elsewhere.

NAE member **Herbert H. Richardson**, Distinguished Professor and chancellor, Emeritus, Texas A&M University System, was a member of the study committee. Paper, $41.00.

Review of NASA's Evidence Reports on Human Health Risks: Letter Report. This is the first in a series of five reports from the Institute of Medicine that will independently review more than 30 evidence reports that the National Aeronautics and Space Administration has compiled on human health risks for long-duration and exploration space flights. This letter report reviews three evidence reports and for each analyzes its overall quality, including readability, internal consistency, source and breadth of cited evidence, identification of knowledge and research gaps, authorship expertise, and, if applicable, response to recommendations from the 2008 IOM letter report, *Review of NASA's Human Research Program Evidence Books*, an initial and brief review of the evidence reports. It also suggests additional sources of expert input.

NAE member **Laurence R. Young**, Apollo Program Professor of Astronautics and professor of health sciences and technology, Massachusetts Institute of Technology, was a member of the study committee. Paper, $31.00.

Sustainable Infrastructure for Life Science Communications: Workshop Summary. Advances in the life sciences—from the human genome to biotechnology to personalized medicine and sustainable communities—have profound implications for the well-being of society and the natural world. Improved public understanding of such advances could benefit both individuals and society through enhanced quality of life and environmental protection, improved K–12 and undergraduate science education, greater understanding of human connections to the natural world, and more sustainable policies and regulations. Yet few systems of support are available to help life scientist communicators share their research with the public or engage the public in discussions about their work. This report is the summary of a two-part workshop convened to identify both infrastructure-related barriers that inhibit or prohibit life scientists from communicating about their work and infrastructure characteristics that facilitate or encourage scientists to engage with public audiences. The report considers communication infrastructure across a range of life science institutions (federal agencies, academia, industry, and nonprofit organizations) and explores novel approaches to facilitate effective science communication.

NAE member **Kristi S. Anseth**, investigator, Howard Hughes Medical Institute, and Distinguished Professor, Department of Chemical and Biological Engineering, University of Colorado Boulder, was a member of the study roundtable. Paper, $40.00.

Limited Affordable Low-Volume Manufacturing: Summary of a Workshop. A workshop was convened by the NRC National Materials and Manufacturing Board to discuss affordable low-volume manufacturing, focusing on the use of commercial off-the-shelf equipment, short production runs, and commercial manufacturing services. Discussions also considered challenges in access to raw materials, affordable process qualification and product certification, the relationship between additive manufacturing and low-volume production, and variable-rate and high-mix manufacturing, two aspects of low-volume manufacturing. The report considers future advances in limited affordable low-volume manufacturing in the United States.

NAE members on the study committee were **David J. Nash**, president, Dave Nash & Associates LLC, and senior vice president, MELE Associates Inc.; **Robert E. Schafrik**, executive, Engineering, Aviation Engineering Division, General Electric Aviation; and **A. Galip Ulsoy**, C.D. Mote Jr. Distinguished University Professor and W.C. Ford Professor of Manufacturing, University of Michigan. Paper, $39.00.

Interim Report of a Review of the Next Generation Air Transportation System Enterprise Architecture, Software, Safety, and Human Factors. The goal of the Next Generation Air Transportation System (NextGen) is to improve the capacity, efficiency, and safety of the US air transportation system and enable reductions in noise, pollution, and energy use. The Federal Aviation Administration and various stakeholders (e.g., equipment providers, airlines, and contractors) are implementing near- and midterm capabilities of this effort. This interim report, part of a larger project to examine NextGen's enterprise architecture and related issues, focuses on challenges of system architecture for software-intensive systems.

NAE members on the study committee were **Steven M. Bellovin**, professor, Department of Computer Science, Columbia University; **R. John Hansman Jr.**, T. Wilson Professor of Aeronautics and Astronautics and director, MIT International Center for Air Transportation, Massachusetts Institute of Technology; **Gavriel Salvendy**, research professor, Louisiana State University; **Thomas B. Sheridan**, Ford Professor of Engineering and Applied Psychology, Emeritus, Massachusetts Institute of Technology; **Robert F. Sproull**, retired vice president and director, Oracle Labs; and **Elaine Weyuker**, software engineering researcher and consultant, Metuchen, New Jersey. Free PDF.

Effects of Diluted Bitumen on Crude Oil Transmission Lines: TRB Special Report 311. The oil sands region of Canada is the source of diluted bitumen shipped by pipeline to the United States, and this report analyzes whether such shipments have a greater likelihood of release from pipelines than shipments of other crude oils. The study committee did not find any pipeline failures unique to the transportation of diluted bitumen nor evidence of physical or chemical properties of diluted bitumen shipments that exceed the range of those of other crude oil shipments. The committee's comprehensive review did not find evidence of any specific aspect of the transportation of diluted bitumen that would make it more likely than other crude oils to cause pipeline releases.

NAE member **Mark A. Barteau**, DTE Energy Professor of Advanced Energy Research and director, Energy Institute, University of Michigan, chaired the study committee. Free PDF.

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