THE POTENTIAL IMPACTS OF 21ST CENTURY OIL AND GAS DEVELOPMENT IN THE APPALACHIAN BASIN:

First Steps Toward a Strategic Research Plan

DRAFT

By the Special Scientific Committee on Unconventional Oil and Gas Development in the Appalachian Basin
December 2014

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SPECIAL SCIENTIFIC COMMITTEE ON UNCONVENTIONAL OIL AND GAS DEVELOPMENT

In early 2014, HEI convened a special scientific committee to explore, define, and assess the potential human health, ecologic, environmental, and social impacts of 21st century unconventional oil and gas development in the Appalachian Basin and to use its assessment to develop a Strategic Research Plan to help guide the study these potential impacts. The committee is chaired by George M. Hornberger, Distinguished Professor of Civil and Environmental Engineering and of Earth and Environmental Science at Vanderbilt University and director of the Vanderbilt Institute for Energy and the Environment. Committee members are highly regarded experts in a variety of disciplines directly related to unconventional oil and gas development and its potential impacts. Special advisors and consultants contribute additional areas of expertise.

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ABBREVIATIONS

NIOSH	National Institute of Occupational Safety and Health
NOx	nitrogen oxides
OSHA	Occupational Safety and Health Administration .
PA DCNR	Pennsylvania Department of Conservation and Natural Resources
PM	particulate matter
STDs	sexually transmitted diseases
VOCs	volatile organic compounds

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- The University of Pittsburgh Institute of Politics provided superior organizational support and guidance with public workshops.

- Advisors to the Committee: Bernard Goldstein of the University of Pittsburgh, Alan Krupnick of Resources for the Future, and Michael Parker of Parker Consulting, who gave generously of their time and expertise in speaking at public workshops, reviewing draft reports, and providing general guidance.

- Gulfport Energy Corporation generously provided the Committee and HEI staff with a tour of its well sites during which knowledgeable Gulfport staff answered questions and showed the equipment, materials, and set-up for drilling and hydraulic fracturing.

- Workshop speakers provided excellent technical presentations: Bernard Goldstein, Rich Haut, Jeffrey Jacquet, Alan Krupnick, Nels Johnson, Mike Parker, and Dan Soeder.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

In the United States and around the globe, the rapid expansion of oil and natural gas production from shale and other tight (i.e., low permeability) geologic formations brings significant opportunity along with questions and controversy about potential effects on people and the environment. With funding from private foundations, the Health Effects Institute (HEI) convened a Special Scientific Committee to develop a strategic plan for guiding research that will answer questions about potential adverse human health, ecologic, environmental, and social impacts of 21st century oil and gas development in the Appalachian Basin (Figure 1).

The phrase "21st century" in this report refers to the Committee's focus on oil and gas development as practiced now and as likely to be modified in the future in response to advancing technology, changing regulations, and other factors. The Committee is considering potential impacts related to all stages of oil and gas development and production that may have impacts on the people, communities, and ecology of the region, including exploration, well pad construction, drilling and completion, production, well closure, and site reclamation as well as all ancillary facilities (e.g., compressor stations, processing facilities, and gathering pipelines) and waste management (e.g., deep well injection, landfilling, and recycling of wastewater) associated with the production of oil and gas.[1] Except where otherwise noted, the

Purpose of this report

This interim report lays the groundwork for the creation of the Committee's Strategic Scientific Research Plan to help guide future research to improve understanding of potential adverse impacts of 21st century oil and gas development in the Appalachian Basin. The phrase "21st century" refers to oil and gas development as practiced now and as modified in the future in response to advancing technology, changing regulations, and other factors. Although the Committee's focus is on research needed to support credible data-driven decision-making about potential adverse impacts on people and the environment, the Committee recognizes that oil and gas development can also generate potential benefits at the local, regional, national, and global levels.

What you will learn from this report

- → The origin and purpose of the initiative
- → The Committee's approach and status of its work
- → A summary of the types of adverse impacts that are potentially related to oil and gas development in the Appalachian region based on the Committee's research expertise, review of hundreds of papers, consultations with many knowledgeable individuals, and tours of gas well sites
- → The Committee's next steps toward development of the Research Plan

What the Committee asks of you

As the Committee turns its attention to research planning, it requests your recommendations for scientific research and the criteria that may be used to prioritize research alternatives.

[1] Potential impacts beyond the region near oil and gas development fall outside the Committee's scope of review (e.g., effects related to distribution and use of oil and gas beyond gathering pipelines, contribution to global climate change).

phrase "oil and gas development" is used in this report to refer to all of these elements of the oil and gas industry in the Appalachian Basin.

The Committee's Strategic Scientific Research Plan will be the result of an impartial, interdisciplinary review and is intended to benefit people living and working in the Appalachian region who want to better understand potential impacts of ongoing oil and gas development. This interim report, a brief summary of the Committee's work to date, lays the groundwork for the Committee's Strategic Scientific Research Plan. More extensive summaries of the literature were developed by members of the Committee to support its research planning deliberations, and they will be available on the HEI website (http://www.healtheffects.org/UOGD/UOGD.htm) in early 2015. With the release of this interim report, the Committee seeks public input on research needs and criteria for prioritizing these needs as it takes the next steps to develop the Research Plan.

This initiative is funded entirely by private foundations in Pennsylvania and West Virginia, including:

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1.1 Origin and Purpose of This Research Planning Initiative

Oil and natural gas development has been occurring in the Appalachian region for more than a century, yet the recent development of unconventional resources represents only a fraction of what is expected in coming years (U.S. Energy Information Administration 2014a). In response to concerns about oil and gas extraction in the Appalachian region, 26 leaders from government, industry, academia, environmental groups, and civil society established the Pennsylvania-based Shale Gas Roundtable (http://iop.pitt.edu/shalegas/). In 2013, this group emphasized the need for "efforts to increase balanced research and rigorous monitoring of the possible impacts of unconventional oil and gas development." HEI's Special Scientific Committee, which produced this Interim Report, was formed as a direct result of the Roundtable's

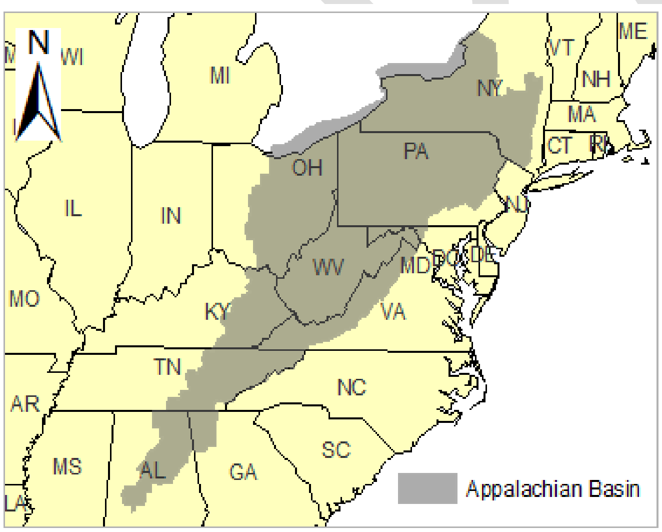


Figure 1. The Appalachian Basin. Source of data: http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/maps/maps.htm

recommendation and brings an impartial, geographically diverse, interdisciplinary perspective to questions about potential impacts.

This interim report summarizes some of the Committee's initial steps toward crafting a Strategic Scientific Research Plan to be released in 2015. The Research Plan will provide an effective foundation for future research, communication, and decision-making by providing an independent, priority-based assessment of key research questions. The Research Plan will include research priorities based on explicit criteria rather than a list of research ideas. It will be designed with the understanding that research planning must periodically be revisited as industry practice evolves, the regulatory environment changes, and scientific understanding grows. The Plan will be a high quality and credible guide to be used by research funders and the scientific community to inform priority-based funding decisions as well as by regulators, oil and gas developers, environmental organization leaders, public health experts, and other stakeholders to inform policy in this important arena.

1.2 EVOLUTION OF OIL AND GAS DEVELOPMENT IN THE APPALACHIAN BASIN

The Appalachian Basin (Figure 1) extends from Alabama northward to New York and from which oil and gas have been extracted since the 19th century, starting with the first commercial gas well drilled in the United States in Fredonia, New York, in 1821, and the first commercial oil well drilled in the Appalachian Basin, near Titusville, Pennsylvania, in 1859. Some controversy arose about environmental impacts that led to a federal court case in the late 1970s (United States v. Minard Run Oil Co., No. 90-12, 1980 U.S. Dist. LEXIS 9570 (W.D. Pa. Dec. 16, 1980), but these concerns rarely rose to the level of public interest evident since the late 2000s, when rarely a day passes that a newspaper headline somewhere does not make reference to some aspect of oil and gas development, frequently hydraulic fracturing (Figure 2).

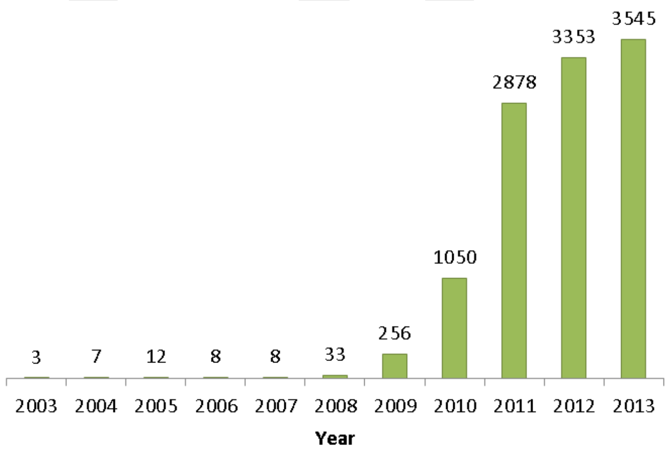


Figure 2. The number of news articles published each year between 2003 and 2013 with the phrase "hydraulic fracturing," as reported by *Environmental Health News*. (Source of data: http://www.environmentalhealthnews.org/; accessed 18-Sep-2014)

Given the historic presence of oil and gas development in the region, why is this new development receiving so much attention now? The scale and rate of development, with nearly 12,000 new wells drilled in Pennsylvania, West Virginia, and Ohio since 2004, differ markedly from previous development, to an extent that has changed the dynamics of the world energy market. This dramatic expansion of oil and gas development stems from technologic changes involving increased use of hydraulic fracturing combined with horizontal drilling to develop low-permeability geologic formations that could not be developed profitably without them. This evolving technology influences where development is economically feasible and enables a substantial increase in the rate of development, the intensity of industrial activity, the requirements for water, chemicals, sand, and other materials, and the productivity that can be achieved. These new and modified practices in turn influence the potential for positive and negative consequences on oil and gas workers, people in nearby communities, the structure and function of their communities, and the local, regional, national, and possibly global environment. People living and working near such development — and even people elsewhere who might be affected by regional air quality impacts now or by similar development locally in the future — have raised many questions about these potential impacts that the Research Plan will address.

1.2.1 Technologic Advances Leading to Rapid Oil and Gas Development in the Appalachian Basin

The Appalachian Basin's oil and gas resources have historically been extracted by drilling vertical wells into underground reservoirs where oil or gas is trapped. This oil or gas flows readily into the vertical well. The development of these conventional resources predominated in the northeastern United States and elsewhere across the country through the mid-1900s. Around 1950, improvements in drilling technology and the expanding use of modern well stimulation techniques to enhance oil and gas recovery prompted the commercial use of such methods in conventional fields across the United States and worldwide (King 2012). Hydraulic fracturing is one such well-stimulation technique that has been used for decades in the Appalachian Basin. Fracturing requires large volumes of water mixed with proppants (sand or other man-made material that keeps the cracks created by the hydraulic fracturing open) and smaller amounts of chemicals. Beginning in the 1980s, hydraulic fracturing allowed for the initial development of unconventional resources in the Appalachian Basin, with the recovery of coalbed methane gas and tight sandstone ("tight sand") gas. These unconventional resources differ from conventional resources in that their lower permeability limits the flow of oil or gas into the wellbore without well stimulation (Figure 3).

The oil and gas in these reservoirs originated from "source rock," which is the geologic formation where it was originally formed from decaying organic matter. Even with the use of hydraulic fracturing to extract oil and gas from conventional and some unconventional formations, it was widely known that a great deal of oil and gas remained in the source rock, with no economically viable method of extracting it. Years of experimentation with horizontal drilling combined with high-volume hydraulic fracturing of unconventional formations yielded success in the Barnett Shale gas fields of Texas and Oklahoma. High-volume hydraulic fracturing differed from early hydraulic fracturing with its requirement for millions instead of thousands of gallons of water per well. These new techniques of horizontal drilling combined with high-volume hydraulic fracturing (Box 1) improved well yields that, in turn, changed the economics of extraction and began to open up development opportunities that had not been economically viable in the past. Experience with drilling horizontal wellbores several thousand feet long and using high-volume hydraulic fracturing led to the widespread development of unconventional oil and gas fields such as the Barnett Shale, Marcellus Shale, and the Bakken Shale (Pierobon 2013).

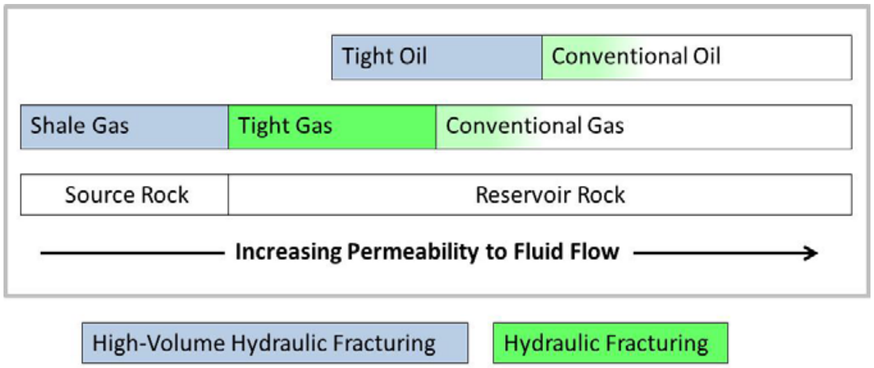


Figure 3. Relationship between the permeability of a geologic formation and the need for hydraulic fracturing or high-volume hydraulic fracturing. The least permeable geological formation is "source rock" where the oil or gas was formed and has remained in place for millennia because of this low permeability. "Reservoir rock" includes a range of subsurface, porous rock bodies of varying degrees of permeability in which oil or gas or both are stored at some distance from the source rock. Well stimulation methods have been used since the late 19th century to facilitate oil and gas flow from reservoir rock. Hydraulic fracturing was introduced in the mid-20th century as a new well stimulation method and has been commonly used to mobilize oil and gas from various types of conventional and unconventional reservoir rocks. Modified from R. Kleinberg, "Unconventional Fossil Fuels" in M.J. Aziz and A.C. Johnson, Introduction to Energy Technology: Depletable and Renewable, Wiley-VCH (in-press).

The successful extraction of oil from the Barnett Shale prompted similar and ongoing development of the natural gas–rich shale formations of the Appalachian Basin. Commercial production from unconventional gas wells began in 2005 in the Marcellus Shale (Geology.com 2005) and in 2011 in the Utica Shale (*http://oilandgas.ohiodnr.gov/production*). From these beginnings, development of the Marcellus and Utica shales has continued in Pennsylvania, Ohio, and West Virginia, with about 12,000 wells drilled since 2004 (Marcellus Center for Outreach and Research; *http://www.marcellus.psu.edu/resources/maps.php*). Neighboring states — New York, Maryland, and Virginia — are still considering whether and how these resources might be developed.

What is "conventional" and "unconventional" in the oil and gas industry?

The terms "conventional" and "unconventional" are widely but not consistently used, creating confusion. Most people use them to distinguish between the geological formations from which oil and gas are extracted. Others use them to classify how oil and gas wells are drilled today. Still others talk about them in the context of emerging oil and gas technology and development. In this report, the Committee uses them as follows:

- → A *conventional geologic formation* is one with relatively high permeability, where the oil or gas have migrated to a reservoir and are held there by a confining rock unit that prevents further migration. Oil and gas flow readily into the wellbore from conventional formations.
- → An *unconventional geologic formation* is one with relatively low permeability (e.g., Marcellus and Utica shales) such that oil and gas do not flow readily into the wellbore without the application of a well-stimulation technique.

Oil and gas are being extracted from wells drilled into both types of geologic formations. Wells in conventional formations (referred to in this report as "conventional wells") vastly outnumber wells in unconventional formations (referred to in this report as "unconventional wells"). However, the scale of development associated with wells in unconventional formations has been the primary source of many of the concerns the public has raised today.

Much public attention has been focused on the use of horizontal drilling and hydraulic fracturing to extract gas from the Marcellus Shale and, to a lesser extent, the Utica Shale. However, the Appalachian Basin is home to other unconventional resources (Figure 4), and the extent to which oil and gas will be extracted from them depends on their viability, the future price of and demand for energy, and the regulatory environment. In addition, horizontal drilling and hydraulic fracturing technologies might be used in the future to improve recovery from conventional oil and gas resources throughout the Appalachian Basin (and elsewhere in the United States).

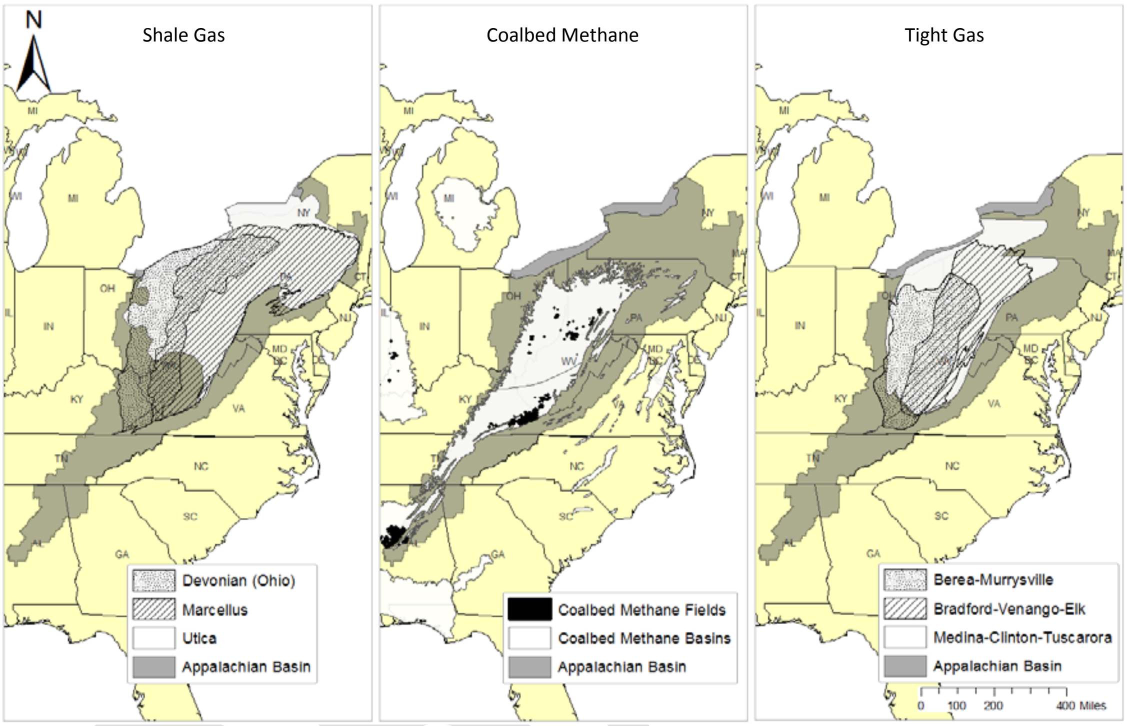


Figure 4. Extent of oil and gas resources in the Appalachian Basin (in gray). : (Left) shale plays (i.e., accumulations of shale gas) (data from 2011), (Middle) coalbed methane fields and basins (data from 2006, 2007 respectively), and (Right) tight gas plays (data from 2010). Source of data: US Energy Administration (U.S. Energy Information Administration 2014b) http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/maps/maps.htm

1.2.2 Contrast Between 21st Century and Earlier Oil and Gas Development

Oil and gas development in the Appalachian Basin before the recent rapid development of the Marcellus Shale involved conventional, and sometimes unconventional, geologic formations from which oil and gas were extracted either without hydraulic fracturing or with a form of hydraulic fracturing that required tens of thousands of gallons of water per well instead of the millions of gallons of water per well used today to support high-volume hydraulic fracturing combined with horizontal drilling. Figure 5 shows the active conventional and unconventional oil and gas wells in Pennsylvania and West Virginia. As can be seen the conventional wells greatly outnumber the unconventional wells. Why, then, have the unconventional wells attracted disproportionate attention and controversy? These wells are far more productive than their earlier counterparts, but they also have a potential for more and different kinds of negative impacts (see Box 1).

Box 1. What is new about oil and gas development in the 21st century?

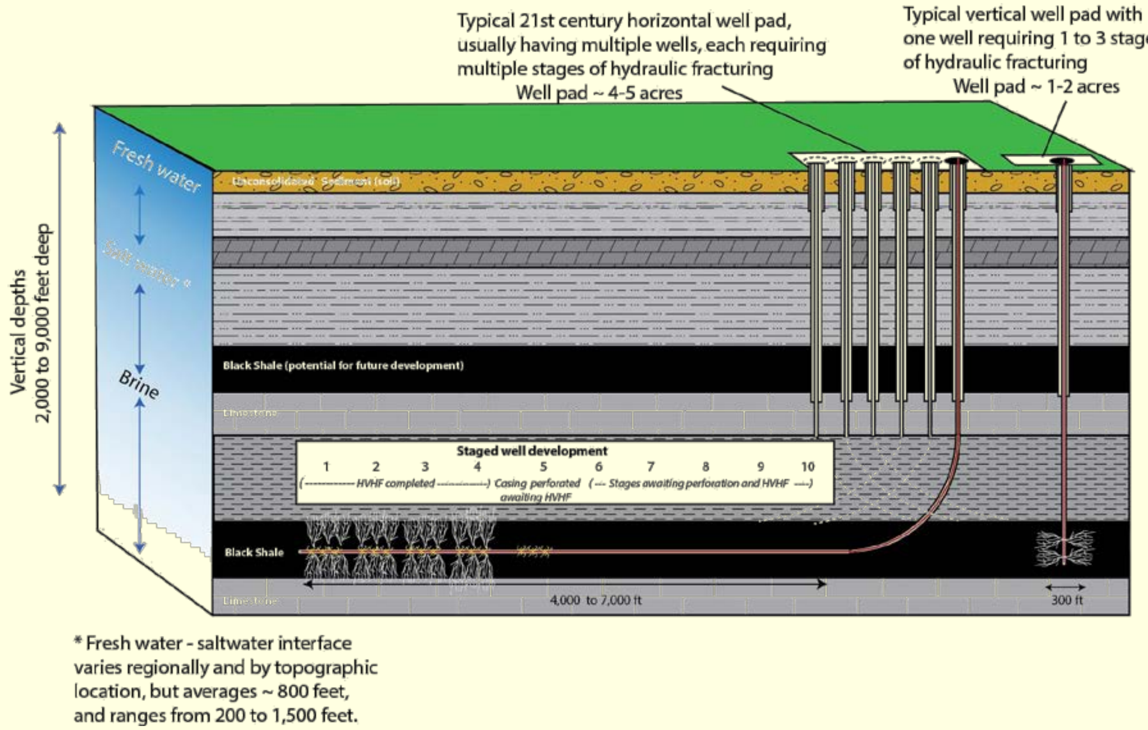
Hydraulic fracturing, horizontal (or directional) drilling, and extraction of oil and gas from unconventional formations, such as tight sandstone and shale, are not by themselves new.

What is new is the use of *high-volume* (millions of gallons of water per well) hydraulic fracturing combined with horizontal drilling (thousands of feet drilled within the target formation) as fracturing methods continue to evolve. This combination of technologic innovations has made previously uneconomical oil and gas resources valuable enough to develop.

Today's oil and gas wells, with their horizontal segments, intersect more of the targeted oil- or gas-bearing rock than earlier vertical wells, which consequently requires the following:

- → Larger well pads with extensive amounts of equipment that must be transported to and from the pad;
- → More raw materials that must be transported to the well pad for drilling, cementing and hydraulically fracturing the target bedrock formation to produce the oil or gas;
- → More liquid and solid waste from multiple wells drilled on one well pad that must be captured, transported, and treated, for reuse or ultimate disposal; and
- → Longer period of industrial activity required at a single well pad when multiple wells developed on it.

In addition, today's oil and gas development sometimes takes place in regions unaccustomed to this scale of development, including regions that range from densely populated to undeveloped forest lands containing the headwaters of many streams and rivers. Development also occurs in areas where groundwater is the primary source of drinking water.



Conceptual layout comparing a vertical well with a horizontal well in the Marcellus Shale. More gas can be recovered from the horizontal well because it allows for multiple stages of fracturing in the productive zone of the shale formation. Only one vertical well is drilled per well pad versus multiple horizontal wells from a single modern well pad. Note: The illustration is not to scale, and actual fracture distances vary by depth and the type of resource under development. Illustration by William Kappel.

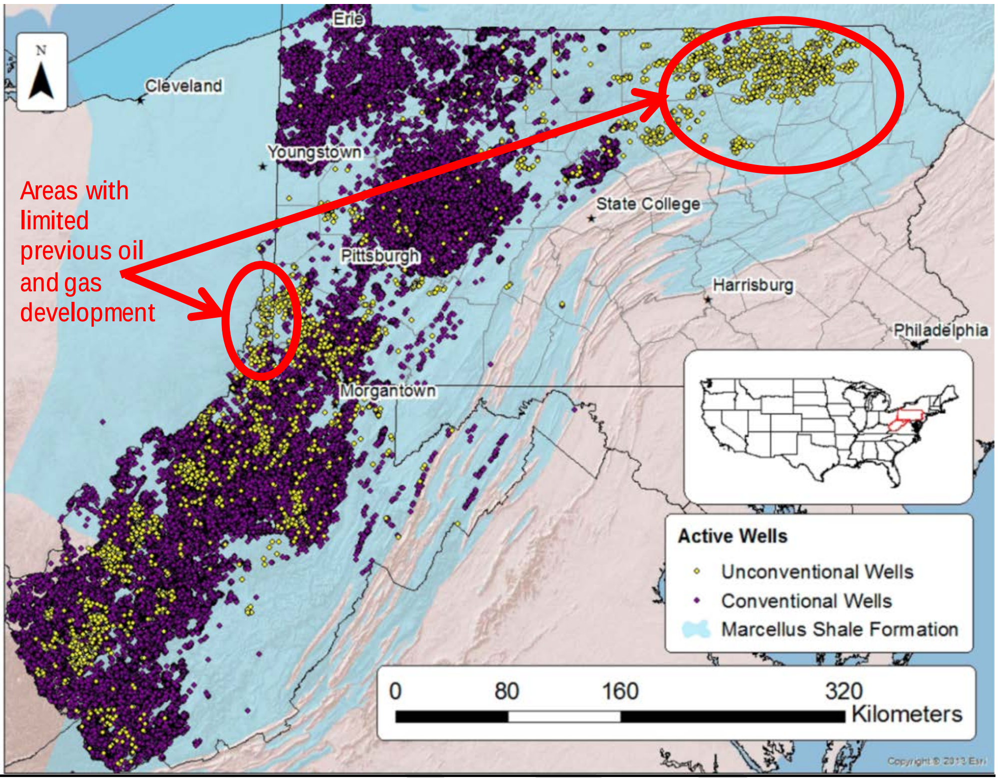


Figure 5. Active unconventional (yellow) and conventional (purple) oil and gas wells in Pennsylvania and West Virginia. Reprinted with permission from Vengosh et al. 2014. Copyright 2014 American Chemical Society.

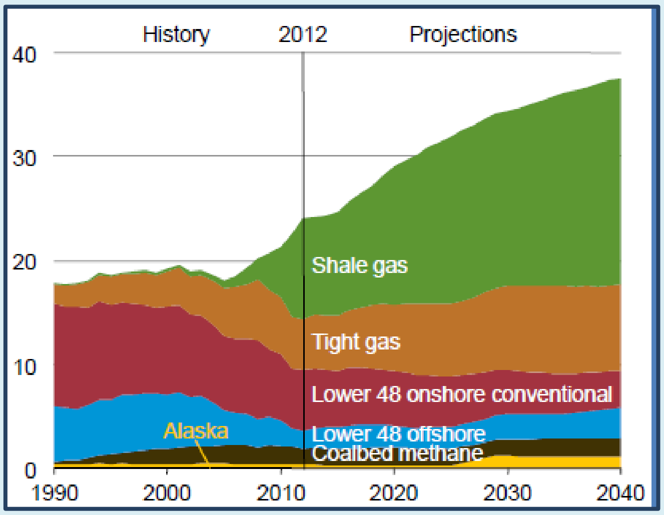
Because of the isolated nature of oil and gas reservoirs, earlier extraction of conventional resources often involved short-term drilling with relatively small drill rigs (e.g., some mounted on a truck). Little or no well stimulation was required to facilitate the flow of oil or gas into vertical wells, there was minimal intrusion of equipment and personnel, and existing pipelines were used to transport the oil or gas. In contrast, the very large, continuous nature of unconventional formations requires longer periods of drilling with larger rigs (as tall as 150 feet), large amounts of ancillary equipment, followed by high-volume hydraulic fracturing. These operations occur around the clock. This new extraction process involves hundreds of truck trips per day to and from a well pad, although trends toward more piping of water to well pads and more recycling of flowback water have been noted. Finally construction of new pipelines, compressor stations, and processing facilities are also required to support the new oil and gas production.

Within the Appalachian basin, the use of the new extraction processes first occurred in northeastern Pennsylvania but has rapidly expanded to include western Pennsylvania, eastern Ohio, and northern West Virginia. Many people living in these regions are familiar with conventional oil and gas development but not with the pace and scale of recent development of unconventional resources. However, in some areas such as northeastern Pennsylvania (Figure 5), the occurrence of large-scale oil and gas extraction is unprecedented. Development of natural gas resources in the Appalachian Basin and elsewhere in the United States is expected to continue increasing over the next 25 years, highlighting the importance of better understanding its positive and negative effects.

The future of natural gas in the United States and the Appalachian region

The United States Energy Information Administration (EIA) predicts a continued and dramatic rise in domestic natural gas production through 2040, with unconventional resources — shale gas and tight gas — responsible for much of the increase.

In 2012, natural gas production from the Marcellus Shale met 16% of domestic demand east of the Mississippi River. EIA predicts that this percentage could rise to 39% by 2022 before declining, although still providing about 31% of demand through 2040. Along with this rising production may come modified transportation patterns, with much of the eastern United States (i.e., east of the Mississippi River) obtaining gas from the Marcellus region instead of Texas, Louisiana, Oklahoma, and the Gulf of Mexico (EIA, 2014).



Historical and projected natural gas production in the United States by source.
Source: U.S. Energy Information Administration 2014a.

2. THE COMMITTEE'S APPROACH AND THE SCOPE OF REVIEW

The Committee's primary objective is to define a priority-based Strategic Scientific Research Plan to guide research in order to better understand the potential adverse human health, social, ecologic, and environmental impacts of 21st century oil and gas development in the Appalachian Basin. The following section of this interim report describes the Committee's general approach and scope of review.

2.1 GEOGRAPHY

The committee is focused on the Appalachian Basin (Figure 1). Much of the discussion about potential impacts from the development of Appalachian Basin oil and gas centers on locations where this development is expanding rapidly in Pennsylvania, Ohio, and West Virginia, but the Committee recognizes the potential for future oil and gas development in other Appalachian states. In devising its Strategic Scientific Research Plan, the Committee will adopt a broader perspective toward development of all types of oil and gas resources throughout the Appalachian region. The Committee further understands that components of its Research Plan will likely be relevant to understanding potential impacts in other regions and will endeavor to create a plan that serves as a template for the evaluation of oil and gas development outside the Appalachian basin.

2.2 OIL AND GAS OPERATIONS AND POTENTIAL IMPACTS UNDER REVIEW

The Committee's research planning to better understand potential impacts on people, communities, and ecologic systems must begin with a clear conception of the oil and gas operations and types of potential impacts that the Committee will review and address in its research plan. This section explains these operations and also provides a more detailed description of the types of potential impacts under review.

2.2.1 Oil and Gas Operations

The extraction technique of high-volume hydraulic fracturing combined with horizontal drilling, which together allow for the current wave of unconventional oil and gas development, are only part of the oil and gas operations that have elicited questions about potential impacts. The Committee is considering potential impacts related to all stages of oil and gas development and production that may have impacts on the people, communities, and ecology of the region, including exploration, well pad construction, drilling and completion, production, well closure, and site reclamation as well as all ancillary facilities (e.g., compressor stations and processing facilities) and waste management (e.g., deep well injection, landfilling, and recycling of wastewater) associated with the production of oil and gas. These stages and the average time required for each one to develop and produce oil or gas from a single well with high-volume hydraulic fracturing are described in Box 2. The development stage for a single well, beginning with exploration and ending with well completion, generally occurs over a period of months, while the production stage can continue for years to decades. However, potential impacts associated with well development can persist for a longer period; for example, when multiple wells are drilled at different times on a single well pad or when multiple well pads are constructed at different times in the same region. Accidents during development can also have long-lasting effects (e.g., uncontrolled surface spills that adversely affect shallow groundwater or nearby surface water bodies).

Box 2. Timeline: Average duration of each stage in the life cycle of a high-volume hydraulically fractured well [1]

Stage	Activities	Time Required	
Exploration	Seismic reflection testing to support selection of a site for oil or gas development	1 to 2 months	Regionally (over 5 square miles), a 3-dimensional survey takes a month or two (not including permitting). Locally (less than 5 square miles), a number of 2-dimensional lines or a small 3-dimensional survey will take days-to-weeks of measurement activity during equipment set-up, local data collection, and subsequent equipment removal.
Site preparation [2]	Construction of well pads, access roads, water-supply systems for drilling and fracturing, and gathering pipelines.	weeks to 1 month	Depends on the distance from local roadways, erosion mitigation measures, and time required to deliver drilling supplies and arrange equipment on the well pad. Designing a water supply system for drilling and fracturing may add additional construction time.
Drilling	Drilling of the topset (vertical part) of a well and setting and cementing of casings	1 to 2 weeks	Depends on the depth of the topset and the length and number of casings and amount of cement needed.
	Drilling of a transition curve and horizontal well and setting and cementing of casings	3 to 4 weeks or more	Depends on the depth of the well, the length of the horizontal leg, the length and number of casings, and amount of cement needed.
	Total drilling time if more than one well is installed on a single well pad	6 months or more	Actual time depends on the number of wells
Well completion (includes hydraulic fracturing and flowback) [3]	Hydraulic fracturing of horizontal well	weeks to ~ 1 month	A week or more to deliver and set-up hydraulic fracturing equipment, and several weeks to perform staged hydraulic fracturing. Each stage requires 30 to 45 minutes, but re-setting subsurface equipment, perforating the casing, and packing off the next stage for fracturing takes 4 to 6 hours. Re-fracturing in the future is possible, but the likelihood and timing depend on many technological and economic factors.
	Preparing the well for production (or shut-in for later production)	days to 1 week	Several days to a week to remove fracturing equipment, flush (flowback) the well of residual materials (i.e., cuttings, proppant, and other debris), and set the production casing. This step can take longer if gas condensates or oil are produced along with the natural gas, resulting in additional equipment needs related to processing and transmission.
	Total hydraulic fracturing time if more than one well is installed on a single well pad	3 months or more	Actual time depends on the number of wells and fracturing stages
Production	Extraction of oil and gas	years to decades	Years to decades; high-volume production for several years followed by reduced production, depending on the depletion curve.
	Processing of oil and gas (compressor stations, gathering facilities, and processing plants)	years to decades	Years to decades; continuous operation
Closure and post-production	Well closure	several weeks	Several weeks to position supplies, material, and drilling rig for closure. A week or more to load the well with brine (to stop gas and fluid flow), remove some of the casings, and cement the well.
	Site restoration; site restoration can occur during production, depending on state law and local custom	Indeterminate	Restoration depends on the lease agreement and whether the site is to be maintained for future development.
Waste Management	Storage, possible treatment and reuse, transport, disposal of liquid and solid waste on or off the well pad	years to decades	About a couple of months for wastes from drilling and hydraulic fracturing; years to decades for wastes from oil and gas production and processing, with quantities diminishing after the first months.

[1] Except where otherwise indicated, this timeline is for oil and gas development and production from a single well; however, a single well pad often includes multiple wells. Therefore, the activity durations at a single well pad with multiple wells would exceed what is reported here. The total time is not proportional to the number of wells because some processes occur in parallel.

[2] This timeline does not necessarily include the time required for constructing gas compressor stations, processing facilities, and waste management facilities.

[3] The amount of time required for hydraulic fracturing depends on the number of times that re-fracturing is technically and economically viable.

Oil and gas industry practices are evolving rapidly and vary as a function of individual operator practice, local regulations, and the geology of the type of oil or gas being extracted. For example, naturally occurring radioactive material is more prevalent in Marcellus shale than Utica shale and, as a result, is not likely to be a concern in all parts of the Appalachian Basin. In some cases, industry practice is changing in direct response to local concerns that have been raised about its potential impacts. In setting research priorities, the Committee will consider the degree to which new practices are evolving in ways that may mitigate or enhance adverse impacts.

2.2.2 Potential Stressors and Impacts

Figure 6 summarizes the Committee's scope of review, including oil and gas development stages, the potential stressors resulting from them, and the potential impacts resulting from the stressors. Individual stressors may lead to multiple impacts. Land development, for example, might lead to landscape disruption and habitat fragmentation as well as damage to community characteristics, reduced infrastructure capacity, and economic stress, which may in turn affect the health and well-being of individuals, communities, and ecosystems. The figure illustrates some of the relationships among oil and gas operations, stressors, and impacts and is not intended to be an exhaustive compilation.

The Committee recognizes the need to distinguish between potential stressors that arise under routine and unexpected conditions (e.g., wastewater spills, vehicle collisions, and well casing leaks). When considering chemicals found in soil, water, air, and other environmental media (e.g., sediment), the Committee also understands the need to distinguish among potential stressors that arise from natural sources, oil and gas development, and other anthropogenic sources. Even under routine conditions there may be periodic excursions when levels of any chemical exposure or other stressor might be higher than average, and the Committee recognizes that these excursions might need to be accounted for in exposure measurement and health studies.

The Committee's evaluation of potential human health effects includes consideration of both short- and long-term effects from exposure to one or more potential stressors associated with oil and gas development. These include, but not limited to, chemical and radiation exposures through water, air, and soil; increased light, noise, and odors; and societal changes. Stresses on regional resources and infrastructure are also being examined. The evaluation of potential ecologic impacts is similar to that being conducted for the human health effects, except that it involves consideration of habitat loss and fragmentation and changes in ecologic community structure (i.e., the organization of and interaction among species that occupy a given area). Potential impacts might be short-lived (e.g., drilling of a single well near an occupied dwelling or a forest) or might persist for decades (e.g., many wells fragmenting a forest or the presence of a processing plant in a rural community). The Committee is focusing its review on the full range of aspects of oil and gas development that could affect the communities, people, and ecologic systems of the Appalachian region. The review is also identifying stressors that might contribute to effects beyond the local area, such as the release of methane to the atmosphere, but the

Committee is not directly evaluating issues such as global climate change, which are already the subject of intense study by other entities.

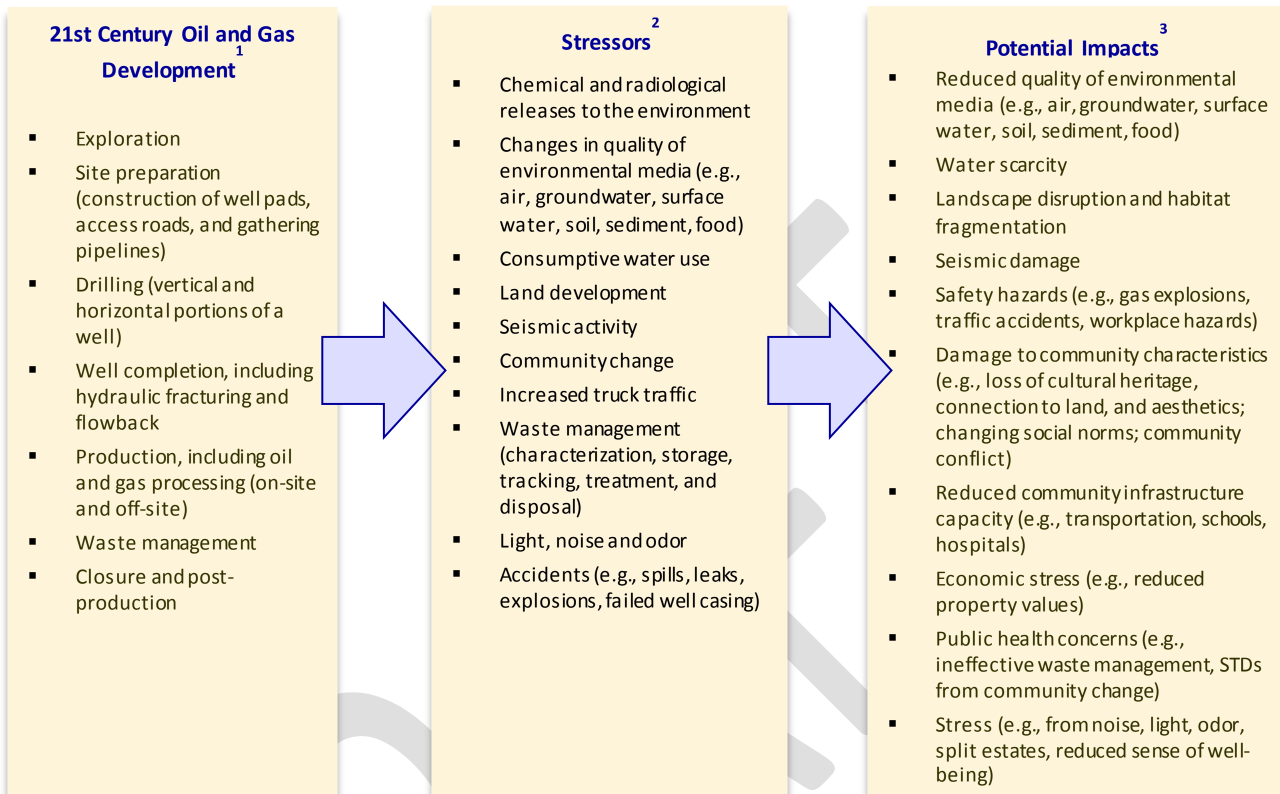


Figure 6. The Committee's scope of review. (Left) *21st century oil and gas development* refers to all stages of development from exploration through well closure and reclamation, and includes waste management and all ancillary facilities such as compressor stations, treatment facilities, and gathering pipelines, but excludes intermediate and interstate pipelines; (Middle) *Potential stressors* are changes to the environment that might lead to adverse impacts on human health, communities, and ecologic systems; (Right) *Potential impacts* are adverse changes that may harm the health and well-being of individual oil and gas workers and members of communities near oil and gas development, the well-being of communities, and the health of ecologic systems. Potential impacts beyond the community and ecologic region near oil and gas development fall outside the Committee's scope of review (e.g., effects related to distribution and use of oil and gas beyond gathering pipelines, and contribution to global climate change).

2.3 Gathering Evidence of Potential Impacts

Since June 2014, the Committee has been gathering evidence of potential adverse human health, social, environmental, and ecologic impacts from all stages of oil and gas development to inform development of its Strategic Scientific Research Plan. The Committee consulted the peer-reviewed scientific literature to develop an understanding of potential impacts from 21st century oil and gas development in the Appalachian Basin. However, given the rapidly changing industry, this literature cannot be expected to include all of the information that the Committee needs to define a sound and relevant Research Plan. For this reason, the Committee is looking beyond the peer-reviewed literature to develop an understanding of current and possible future industry practice as it pertains to potential adverse impacts.

2.3.1 Scientific Literature and Technical Reports

The Committee reviewed more than 800 articles and reports with information relevant to oil and gas development in the Appalachian region (Appendix C), and some Committee members prepared synopses that will be posted at HEI's website (http://www.healtheffects.org/UOGD/UOGD.htm) in early 2015.

Some of these reported studies and data directly relate to developing Appalachian Basin resources, while others provided information from other geologic basins of potential relevance to the Appalachian Basin. In compiling its review, the Committee gave priority to peer-reviewed articles from the scientific literature as well as reports and data from non-governmental research institutions and government agencies that oversee oil and gas development and production in the Appalachian region. Findings from some of the currently available literature might not be relevant under future development conditions given the changes in oil and gas industry practice and its regulation, but they might be important for understanding previous and potentially long-lasting impacts of past and current practices. The Committee's review and evaluation of the scientific literature will continue as it formulates the Strategic Research Plan.

2.3.2 Briefings by Experts

Committee members bring relevant knowledge and experience to research planning, with expertise in many disciplines ranging from geophysics and petroleum geology to epidemiology, medicine, aquatic ecology, and sociology. Nevertheless, the Committee consulted subject matter experts to develop a deeper understanding of current industrial practice. Specifically, experts have briefed the Committee through meetings and webinars on unconventional oil and gas geology and industrial practices in the Appalachian Basin and on trends in industry practice, particularly fracturing methods.

2.3.3 Public Workshops

As part of its review, the Committee, with organizational support provided by the University of Pittsburgh Institute of Politics, is hosting three public workshops to hear from a wide variety of experts and government officials, as well as from industry, community, and environmental groups, to ensure that it considers the full range of issues and questions. The first public workshop occurred in June 2014 in Pittsburgh, Pennsylvania, where participants included academic scientists, federal and state officials, representatives of industry working actively in the region, and leaders from nongovernmental organizations evaluating ecologic and human health concerns, some of whom are working directly with local communities proximate to natural gas operations to understand potential impacts. The workshop also included a series of technical talks that addressed the technology of oil and gas development; potential implications for human health, communities, and the environment; and recommendations for scientific research to understand these implications. A second public workshop is being held on December 10, 2014 in Wheeling, West Virginia, in conjunction with the release of this interim report, and before the Committee turns its attention to research planning. This workshop will provide another opportunity for stakeholder input and will include technical presentations on potential social impacts of oil and gas development and on current and possible future industry practice. The final public workshop will be held following release of the draft Strategic Scientific Research Plan in mid-2015 to provide for more input from stakeholders.

2.3.4 Tour of Gas Well Sites

In August 2014, the Ohio County Health Department in northern West Virginia provided HEI staff with a roadside tour of gas well sites, compressor stations, and a large processing plant in West Virginia. In September 2014, Gulfport Energy Corporation provided the Committee with a tour of well pads in southeastern Ohio set up for drilling a 17,000-foot well (combined vertical and horizontal length) and for high-volume hydraulic fracturing (Figure 7). These two tours conveyed important information about current industry practice; however, the Committee recognizes that they cannot be relied upon to understand the tremendous variability in practice over time and among various developers and regions. In addition, some of the committee members have also toured and worked on many additional facilities as part of their other professional activities.

Figure 7. HEI's Special Scientific Committee on Unconventional Oil and Gas Development in the Appalachian Basin inspects a hydraulic fracturing operation in southeastern Ohio on September 8, 2014. The company developing these wells hosted the tour.

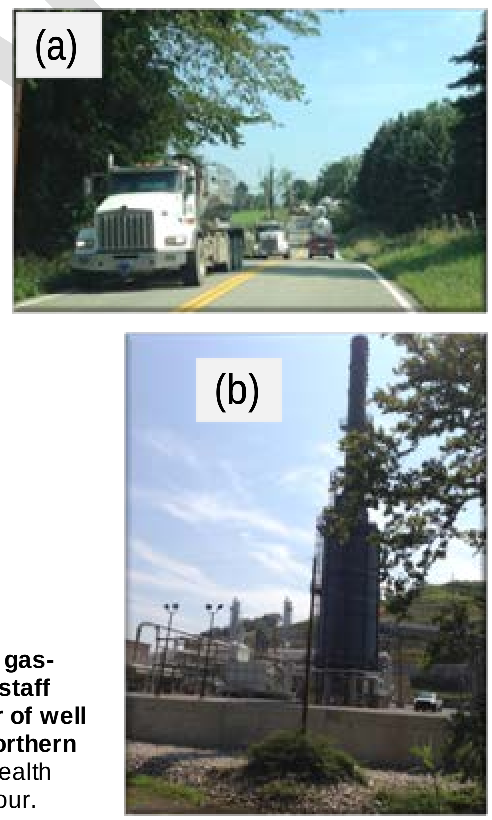


Figure 8. Gas well–related traffic and a gas-processing facility as observed by HEI staff during an August 1, 2014, roadside tour of well pads and gas-processing facilities in northern West Virginia. Staff of the Ohio County Health Department in Wheeling, WV hosted the tour.

2.4 The Committee's Review in the Broader Context of Energy Policy

Although the Committee's focus is on research needed to bring credible data-driven analysis to answering questions about potential adverse impacts on people and the environment in the Appalachian region, the Committee recognizes that oil and gas development can also generate potential benefits at the local, regional, national, and global levels. The energy needed in the United States and around the world will inevitably come from a range of sources, and the actual benefits and impacts resulting from energy generation and use will hinge on the combination of energy alternatives actually used. Agencies and others at the regional, national, and international levels are actively engaged in the complex task of evaluating various energy source combinations, including a consideration of the climate change potential of various scenarios. Given those broader analyses, the Committee has sought to answer a more focused but critical question to inform future energy policy choices — which potential adverse impacts of oil and gas development warrant priority consideration for scientific study? This report presents the Committee's first steps toward answering this question.

3. Potential Stressors and Impacts

This section briefly summarizes the Committee's review of the potential stressors and impacts of oil and gas development in the Appalachian Basin on people and the environment. The summary is based on the Committee's review of hundreds of peer-reviewed scientific papers and reports, all of which are listed in Appendix C. More extensive synopses of the literature were developed by members of the Committee to support its research planning deliberations; the synopses will be available on the HEI website (http://www.healtheffects.org/UOGD/UOGD.htm) in early 2015.

This section is not intended to convey the potential impacts that the Committee regards as most important. Rather, it reflects the impacts that have received attention in the peer-reviewed literature; consequently, it might not include all the potential stressors and impacts that might ultimately receive attention in the Committee's research planning. For example, much literature has focused on potential impacts during the well development phase, notably well construction, drilling, and fracturing. The section reflects this focus with, consequently, less discussion of potential impacts from the production and post-production phases. Also, industry practices can vary considerably across the region as a function of local geology, regulatory requirements, and company practices. These variations can affect the potential stressors and impacts that might occur.

3.1 ENVIRONMENTAL STRESSORS

This section summarizes potential environmental stressors that may arise from 21st century oil and gas development. The discussion of potential stressors is organized by the stage of oil and gas development and production to gain a better understanding of when and how each potential stressor occurs. First, however, a brief subsection summarizes potential stressors involving emissions to air because they are present during many or all stages of oil and gas development and production.

3.1.1 Potential Stressors Related to Air Emissions

There are several recent reviews on air impacts from unconventional oil and gas development, production, and processing (Allen 2014; Field et al. 2014a; Moore et al. 2014a). Data on air emissions exist for many sources of air pollution associated with the industry, including diesel engines, natural gas engines, natural gas turbines, and natural gas–fired heaters, allowing for preliminary assessments of air quality impacts. Many oil and gas studies to date have focused on measurements of total emissions near well pads but were not organized by stage of development.

At the local level (i.e., near the well operations), multiple studies have reported evidence for increased emissions of particulate matter (PM), volatile organic compounds (VOCs), and air toxics in both Appalachian and other areas (Gilman et al. 2013; Helmig et al. 2014; Milton et al. 2014; Pétron et al. 2012; Rich et al. 2013; Pekney et al. 2014; Bunch et al. 2014; McCawley 2013; Zielinska et al. 2010). These emissions are specific to certain stages of development.

At the regional level, there is substantial evidence that oil and gas activities have increased concentrations of ozone precursors, especially petroleum hydrocarbons (Katzenstein et al. 2003;Gilman et al. 2013) and potentially NO_2 (Caulton et al. 2014), but published data do not indicate that unconventional oil and gas development has led to increased ozone levels in the Appalachian basin. In fact, monitoring data collected in urban areas indicate that ozone levels in most of the Eastern United States have decreased over the last decade due to implementation of regulations that have reduced emissions of VOCs and NO_x from power plants, motor vehicles, and other sources. These regulations have not yet been fully implemented; continued implementation is expected to further reduce ozone levels. Emissions from unconventional oil and gas development may offset some of these reductions as opposed to leading to higher ozone levels. Therefore, the fact that ozone levels are decreasing does not mean oil and gas activities are not affecting ozone levels. Roy and colleagues (2013) performed simulations to investigate the effects of development in the Marcellus formation on regional ozone levels. Simulations for the year 2020 showed that the best estimate emissions scenario raised maximum daily eight-hour ozone concentrations by as much as 5 parts per billion by volume (ppbv) on high ozone days relative to a scenario with no Marcellus development.

At the global level, questions have arisen about the emissions of methane, a potent greenhouse gas, at all stages of the production, development, distribution and use cycle for natural gas.

These important questions are already the subject of extensive efforts to characterize their emissions (e.g. Allen et al 2013; Brandt et al 2014; Alvarez et, 2014) given that attention, and the fact that the scope far exceeds potential impacts in the Appalachian region, this Committee did not specifically address global emissions questions other than to note the potential for emissions at each stage of the process.

3.1.2 Potential Stressors Related to the Development Phase

The oil and gas development phase consists of the following general stages: exploration, site preparation, drilling, and well completion, including hydraulic fracturing. Potential stressors specific to each stage are summarized in this section.

As noted earlier, a variety of potential air quality impacts can arise during the site preparation stage that then continue for several or all stages of the development phase (Table 1). Heavy duty diesel engines used in construction equipment and trucks can emit nitrogen oxides (NO_x), particulate matter (PM), volatile organic compounds (VOCs), and air toxics[2], although newer diesel engine technology is significantly reducing these emissions. Dust is also a potential air quality concern during the construction phase.

Table 1. Important air emission sources during the development of a 21st century oil and gas well.

Source Category	NO_x	VOCs	PM	Air Toxics	Climate Forcers[a]	Quality of Emissions Data
Diesel engines in drill rigs, frac pumps, trucks, generators, etc.	•	•	•	•	•	Medium
Natural gas engines in drill rigs, frac pumps, vehicle, generators, etc.	•	•	•	•	•	Medium
Dust from vehicle traffic, site construction, etc.			•			Fair
Fugitive emissions during drilling, hydraulic fracturing, and completion		•		•	•	Fair
Completion venting		•		•	•	Fair
Storage tanks		•		•	•	Fair
Waste impoundments		•		•	•	Poor
Flares	•	•	•	•	•	Poor

[a] Gases or particles that alter the Earth's energy balance by absorbing or reflecting radiation.

[2] A list of 186 hazardous air pollutants is specified in the Clean Air Act Amendments of 1990. The list includes VOCs such as benzene, formaldehyde, and other pollutants, such as diesel PM (*http://www.epa.gov/ttn/atw/188polls.html*).

Exploration

> What happens during this stage?
>
> Seismic reflection testing, which is used to support selection of a site for oil or gas development.
>
> How long does it take?
>
> → Regionally (over 5 square miles), a 3-dimensional survey takes a month or two (not including permitting). Locally (less than 5 square miles), a number of 2-dimensional lines or a small 3-dimensional survey will take days-to-weeks of measurement activity during equipment set-up, local data collection, and subsequent equipment removal.

During the exploration stage, developers seek optimal locations for developing oil and gas wells. Seismic reflection surveys can be used for this purpose. These surveys produce a three-dimensional image of subsurface geology by measuring seismic wave vibrations that are propagated into the earth, with vibrators mounted on trucks or shallow explosive charges, and reflected back to the surface. The three-dimensional image or two-dimensional cross section can show the geologic section, and naturally occurring structure (faults and folds) in the rock formations. These surveys can involve several potential stressors, including noise, vibration, vehicle emissions, habitat fragmentation, and landscape pattern changes.

Site Preparation: Construction of Well Pads, Access Roads, Water Supply System, and Pipelines

> What happens during this stage?
>
> Site preparation includes the construction of well pads, access roads, gathering pipelines, and water-supply systems for drilling and fracturing
>
> How long does it take?
>
> Several weeks to a month, depending on various factors:
>
> → Distance from local roadways
> → Erosion mitigation measures
> → Location of water supply

The construction phase involves creation of access roads, well pads, rights-of-way for pipelines, etc. The impacts are similar to those associated with other large-scale construction projects. Land disturbance during this stage can lead to changes in wildlife habitat, surface water hydrology and the capacity to handle stormwater events. Stormwater from oil and gas sites can cause erosion and can carry pollutants (e.g., oil and gas from vehicles and machinery, phosphorus from soil disturbance, and suspended sediment) both to surface water and shallow groundwater (Rahm and Riha 2014; Olmstead et al. 2013).

Well Construction and Drilling

Well construction includes the selection of various steel casings and cement layers whose primary goal is to protect the wellbore's integrity for decades (Figure 9). These components are selected based on site-specific subsurface conditions, including the type of rock layer, temperature, expected pressures, and composition of the fluids encountered at depth. The efficacy of well construction best practices is specific to each well, and the extent to which best practices are employed is not well-known.

Well integrity issues have been reported in conventional and unconventional oil and gas wells at various developmental stages (e.g. construction, production, and post-production) and in various geographic settings (Davies et al. 2014; Vidic et al. 2013). Leakage of gas in a Marcellus well was caused by channeling through the cement (Figure 10), for example, in a case where the cement did not have the properties specified in the design (Moore et al. 2012).

> What happens during this stage?
>
> - → Drilling and construction of <u>one</u> topset (vertical part) of a well
> - → Drilling and construction of <u>one</u> transition curve and horizontal well
>
> How long does this stage take for one well?
>
> - → Topset: A week or two of drilling, depending on the depth of topset well and the length and number of casings and amount of cementing needed
> - → Transition curve and horizontal: About three to four weeks or more of drilling and setting and cementing of casings; actual duration depends on depth of well and length of horizontal leg.
>
> The time required increases with multiple wells

In parts of the Marcellus region, there is evidence of thermogenic[3] methane migrating into freshwater aquifers from shale and from leakage from more shallow sources (biogenic[4] methane) using geochemical tracers (Vengosh et al. 2014, Osborn et al. 2011, Jackson et al. 2013a, Molofsky et al. 2011, Molofsky et al. 2013, Warner et al. 2012). In Pennsylvania, naturally occurring thermogenic methane has been found to be widespread in shallow groundwater (Baldassare et al. 2014; Molofsky et al. 2013), but increased levels of thermogenic methane in Marcellus area water wells have been linked in some cases to inadequate cement seals, failures of the annulus, faulty casings, and underground gas well failure (Osborn et al. 2011; Darrah et al. 2014). However, (Hammack et al. 2014) sampled for two months before and for eight months after the hydraulic fracturing of six wells in the Marcellus region, monitoring gas migration using a variety of techniques, and, to date, they have found no evidence of gas migration or brine migration from the Marcellus shale formation to shallower formations. The potential for gas migration is dependent not only on well construction, but also on underlying geology, topography, and preexisting fracture systems (Vengosh et al. 2014).

Another potential environmental impact concerning wellbore integrity during the drilling process is the possible migration of saline formation fluids into freshwater aquifers. Indirect studies, however, have suggested that increased drilling activity is not associated with changes in the isotopic composition of shallow aquifers (Vengosh et al. 2013); the Committee was unable to find more direct studies. Contamination at the ground surface also could potentially reach freshwater aquifers by way of an inadequately cemented wellbore.

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[3] Thermogenic methane is produced by intense heat and pressure applied to organic-rich bedrock such as the Marcellus shale. In order for thermogenic methane to reach groundwater aquifers, it must migrate through a natural fracture system or through pathways created by compromised wellbore integrity (See Figure 10).

[4] Biogenic methane is produced by microbes as they decompose organic matter, which is usually from surficial sources (e.g., naturally buried organic material, landfills, or septic systems).

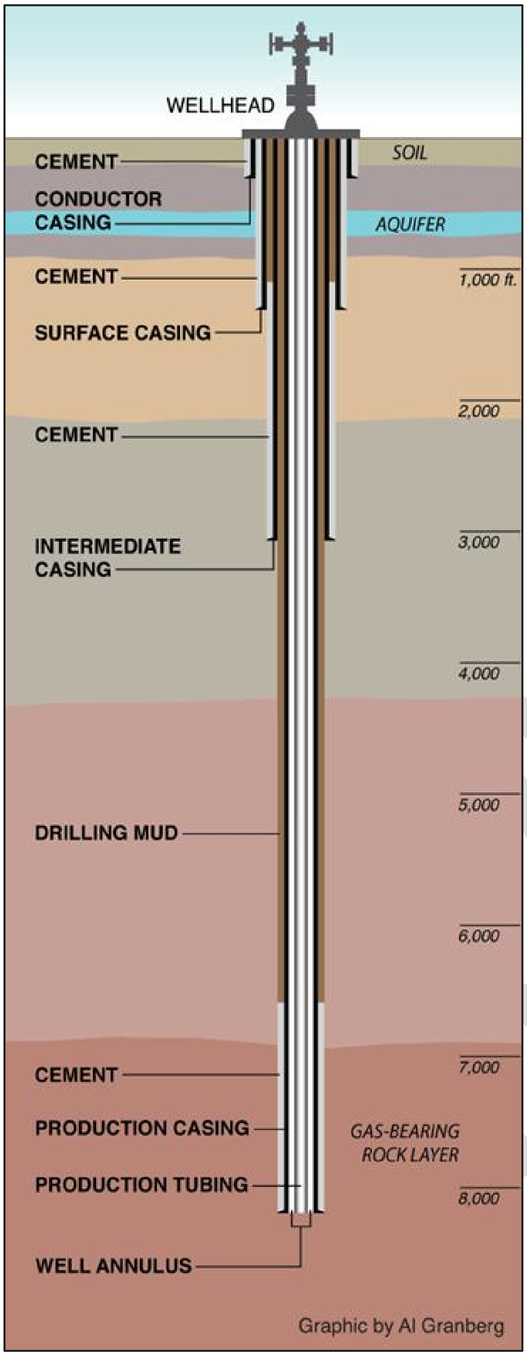

Figure 9. Idealized diagram of vaious types of well casing. The conductor casing provides a solid foundation for equipment attached to the top of the well. The surface casing provides the primary protection for fresh water aquifers and must extend to a depth that protects the deepest drinking water aquifer. The intermediate and production casing cover the wellbore to the depth needed or to the rock layer with productive gas. Al Granberg/ProPublica. Reproduced from Granberg 2009.

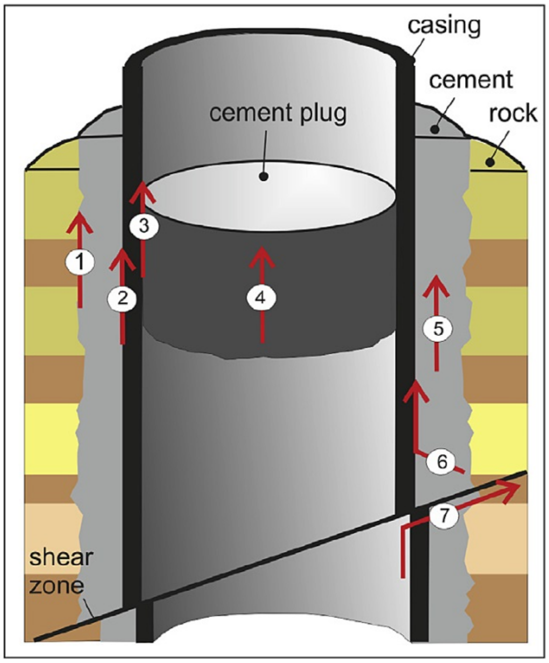

Figure 10. Routes for fluid leaks in a cemented wellbore. (1) Between the cement and the surrounding rock formations. (2) Between the casing and the surrounding cement. (3) Between the cement plug and the casing or production tubing. (4) Through the cement plug. (5) Through the cement between the casing and the rock formation. (6) Across the cement outside the casing and then between this cement and the casing. (7) Along a sheared wellbore (i.e., one that has been displaced [sheared] sufficiently by movement in the ground so as to split the casing). Davies et al. 2014

Drilling an oil or gas well produces waste in the form of drilling muds and drill cuttings. These wastes can contain original components of drilling fluids as well as brine, rock, naturally occurring radioactive materials, and other chemical components present in the target and overlying formations. There is also the potential for spills of drilling fluids onto the ground surface. A discussion of the on-site waste storage and transport of waste to offsite treatment locations can be found, in the Waste Management section.

Diesel engines used in drill rigs, generators and other equipment are known to emit air pollutants (see above). Elevated methane emissions have also been measured at well pads during the drilling phase (Caulton et al. 2014). Methane is not directly toxic to humans; however, it is a climate forcer and thus has a direct impact on global air quality and climate. Gas vented during the drilling phase can also contain air toxics, such as single ring aromatics Field et al. 2014b. Although methane emissions from oil and gas infrastructure are an important global concern, as noted above, they are beyond the scope of the Committee's review.

Drilling occurs 24 hours a day, seven days per week until the well is completed, usually on the order of weeks depending on the number of wells. This constant activity is associated with the potential stressors light, noise, and traffic flow, which are particularly noticeable at well pads in rural areas.

Well Completion (Including Hydraulic Fracturing and Flowback)

Once the targeted depth of the well is reached and the casing is cemented in place, the well is ready to be completed. The completion process involves perforating the casing, cleaning the perforations, hydraulically fracturing the targeted rock formation, and "flowing back the well" to remove materials used for hydraulic fracturing and to determine its economic viability.

Hydraulic fracturing requires large amounts of water, on the scale of 1 to 6 million gallons per well. The transport of this water to the site can be accomplished by way of trucks or pipelines. Pipeline-related impacts will be discussed in Section 3.2. The other potential impacts of freshwater use for hydraulic fracturing include issues related to transport by truck (e.g., emissions, traffic accidents, noise, and road wear) and unsustainable water use. Although water scarcity is typically not an issue in the Appalachian region, fracturing operations use a substantial amount of surface water and have been

What happens during this stage?

- → Hydraulic fracturing of horizontal well
- → Preparing the well for production (or shut-in for later production

How long does it take for one well?

- → Hydraulic fracturing: A week or more to resupply the site with fracturing equipment and materials and to setup and test the equipment. Several weeks to do 'staged' hydraulic fracturing, depending on the number of stages and length of the horizontal.
- → Preparing for production: Several days to a week to remove fracturing plugs, flush (flowback) the well of residual materials (i.e., cuttings, proppant, and other debris), and set the production casing. (This step can take longer if gas condensates or oil are produced along with the natural gas, resulting in additional equipment needs related to processing and transmission)

The time required increases with multiple wells

shown to dramatically reduce base flows in small streams (Rahm and Riha 2014).
Hydraulic fracturing fluids combine large volumes of water with chemicals and proppant to achieve maximum production of oil or gas. The mixture of chemicals depends on the geology of the rock being fractured and on the purpose of the fracturing stage (e.g., maximizing proppant suspension, placing propping materials firmly in induced fractures,). Recent research has identified the detailed chemical composition of selected fracturing fluid samples (Stringfellow et al. 2014). Some of these chemicals can have carcinogenic, endocrine-disrupting, and other toxic properties (Stringfellow et al. 2014; Colborn et al. 2011; Kassotis et al. 2013); however, whether the chemicals affect the environment or human health depends on the magnitude, frequency, and duration of exposure.

The on-site mixing and storage of fracturing fluids and related chemicals creates the potential for spills and the subsequent contamination of surface water and groundwater. Multiple studies have shown that spills and, in particular, spills of fracturing fluids, flowback fluids, and produced water (see below) are the most frequently reported violations in Pennsylvania (Considine et al. 2012; Rahm and Riha 2014). The occurrence and frequency of spills appears to correlate with the density of hydraulically fractured wells in the Marcellus region (Figure 11). Limited measurements are available to assess the environmental contamination resulting from fracturing fluid spills.

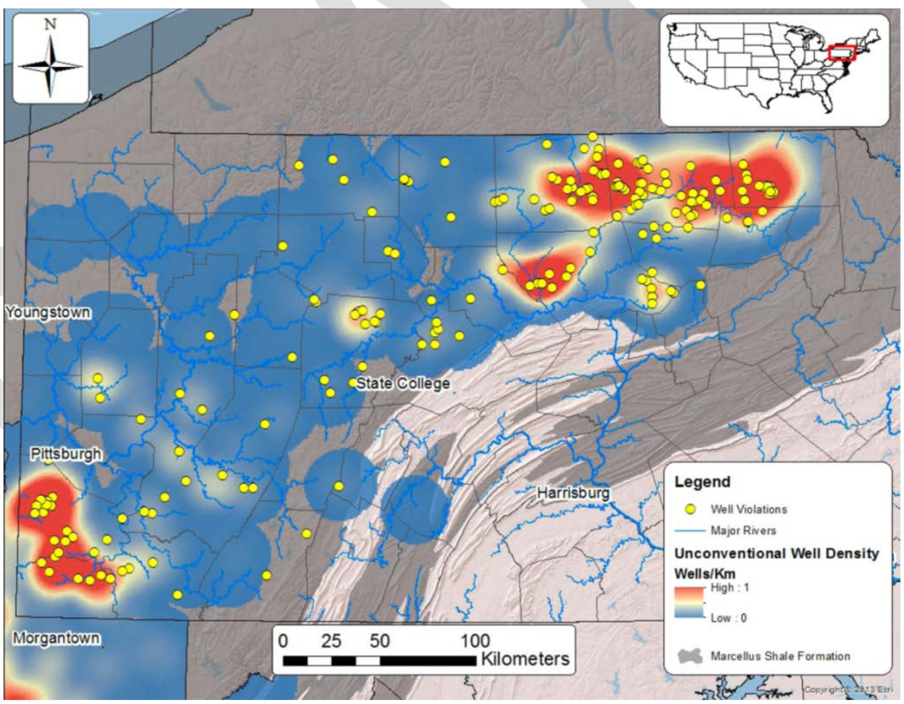

Figure 11. Density of unconventional well drilling and occurrence of reported environmental violations in Pennsylvania. Warm colors (red) represent areas of higher density of unconventional well drilling; cooler colors (blue) represent areas of lower density. Unconventional wells with reported violations of a release to the environment are shown by yellow dots. Violations include discharge of industrial waste to streams; drill cuttings, oil, brine and/or silt, discharged without a permit; and polluting substances discharged to waterways. Reprinted with permission from Vengosh et al. 2014. Copyright 2014 American Chemical Society.

After fracturing fluids are mixed, they are injected at high-pressure into the subsurface in a series of stages that causes microfractures in the shale formation in the immediate vicinity of the horizontal wellbore. This step has been suggested as a mechanism for induced seismic events (i.e., seismic events attributable to anthropogenic sources). Only one incident of seismic activity that can be considered earthquake activity in North America (in Oklahoma) has been likely linked to hydraulic fracturing (National Research Council 2013). As reported by multiple reviews, hydraulic fracturing is typically responsible for earthquakes of very small magnitude (micro-seismic events) and not potentially damaging activity (Davies et al. 2013; National Research Council 2013; Jackson et al. 2014). This activity should be distinguished from the seismic activity that has been associated with deep-well injection of waste waters (see the Waste Management section below). In addition, the creation or existence of fractures does not necessarily lead to faulting, or fault movement, that can cause seismic events that, in turn, might be related to earthquake activity.

Groundwater contamination directly related to fracture networks created by hydraulic fracturing is possible, but not likely. Research to date in the Marcellus region and beyond suggests that fractures can extend to a maximum of 600 m above the horizontal wellbore — a height that in most circumstances is well below freshwater aquifers (Figure 9; Davies et al. 2012; Fisher and Warpinski 2011). However, evidence also suggests that the migration of fractures and fracturing fluid in the subsurface can be facilitated by pre-existing fracture networks. No evidence was found of fractures created by the hydraulic fracturing process leading to thermogenic methane or target rock brine contamination in water wells. A number of recent articles have reviewed this topic (Vengosh et al. 2014; Flewelling and Sharma 2013; Jackson et al. 2013b). A more likely pathway for groundwater contamination during hydraulic fracturing is a change in wellbore integrity caused by fracturing pressures, which can in turn potentially open migration pathways for thermogenic or biogenic methane from below and other fracturing-related chemicals from above into groundwater (Soeder et al. 2014). See the Well Construction and Drilling section above for additional discussion of methane migration.

The pumps that pressurize fracturing fluids are powered by diesel engines, which emit NO_x, VOCs, PM, air toxics, and climate forcers (see above). One respirable pollutant that is unique to the fracturing stage is silica, which is a proppant mixed with water and other chemicals to create fracturing fluid. Typically millions of pounds of sand are used in each well, and the importance of controlling worker exposure to silica has been recognized (https://www.osha.gov/dts/hazardalerts/hydraulic_frac_hazard_alert.html).

Fracturing of the target geologic formation can take as long as several weeks for a single well, depending on the number of stages fractured in a horizontal well (Box 1). In the first one to two weeks after a well has been hydraulically fractured, a period of "flowback" occurs, when fracturing fluid constituents (10 to 40% of the original fracture fluid volume in the Marcellus formation) return to the surface along with brines (salt) and total dissolved solids characteristic of the target formation. This flowback water must be stored on site, possibly treated for re-use, or treated partially or not at all and transported for treatment, reuse, or disposal elsewhere. Potential impacts during flowback include chemical volatilization (e.g., methane, VOCs, and air toxics) that affect air quality (via completion venting), spills, leakage to groundwater from holding ponds, flooding from storm events, and spills or accidents during fluid handling on site and transportation offsite. Wastewater might be disposed of off-site in underground injection wells, and this form of disposal can also induce seismic activity in the subsurface by activating naturally occurring faults (National Research Council 2013). Flaring of gas can also emit NO_x, VOCs, methane, and air toxics. Concerns about groundwater are similar to those for fracturing fluids (see above). To date, there is no evidence of groundwater contamination via migration of flowback water through fractures created by the hydraulic fracturing process (Vengosh et al. 2014).

Like drilling, hydraulic fracturing occurs 24 hours a day, seven days a week until complete, usually on the order of weeks to a month. Also like drilling, this activity is associated with the potential stressors light, noise, and traffic flow, which are particularly noticeable at well pads in rural areas. There have also been some reports of odors associated with hydraulic fracturing.

3.1.3 Production

The production stage of a well usually covers several years to decades of operation. After the initial flowback period (one to two weeks after hydraulic fracturing), and despite the fact that no water is used during this stage, water continues to return to the surface, usually in diminishing quantity, and its chemical makeup is more affected than flowback water by the geologic formation that was fractured. This water is known as produced water and can be more contaminated than flowback water. Produced water typically has higher total dissolved solids than flowback water does and contains hydrocarbons, heavy metals, and possibly naturally occurring radioactive materials. In addition, radium (a naturally occurring radioactive material) has been measured in produced water at concentrations above those of standards for drinking water and industrial effluent (Haluszczak et al. 2013; Rowan et al. 2011).

> What happens during this stage?
> - → Production of oil or gas from the well
> - → Compression and processing
>
> How long does this stage take?
> - → High-volume production lasts for several years, depending on depletion curve
> - → There are one or more decades of reduced production

Wellbore integrity issues increase with the age of oil and gas wells (Brufatto et al. 2003), creating risks for groundwater contamination and leakage of methane and other VOCs as discussed in the Well Completion section.

Facilities and equipment associated with the production stage can emit air pollutants (Robinson 2013). Compressor stations, wellhead compressors, gathering and processing plants, and ancillary equipment such as heaters, dehydrators, separators, liquid storage tanks, flares, and pneumatics each emit some or all of the following: NOx, VOCs, PM, air toxics, and climate forcers (Table 2). Unlike the drilling and fracturing stages, this stage – and associated emissions - can continue for years to decades. Potential impacts include changes in local, regional and global air quality.

Table 2. Important air emission sources during the production stage of a 21st century oil and gas well.

Source Category	NO_x	VOCs	PM	Air Toxics	Climate Forcers[a]	Quality of Emissions Data
Natural gas engines and turbines used to drive compressors	•	•	•	•	•	Medium
Vents at compressor stations, processing facilities, well sites, etc.		•		•	•	Medium
Fugitives associated with liquid unloading, pressurized equipment, etc.		•		•	•	Poor
Processing and treatment equipment such as heaters, dehydrators, and separators	•	•	•	•	•	Fair
Blow down venting		•		•	•	Poor
Storage tanks		•		•	•	Poor
Gas-driving pneumatics		•		•	•	Fair
Flares	•	•	•	•	•	Poor

[a] Gases or particles that alter the Earth's energy balance by absorbing or reflecting radiation.

In addition to impacts on air quality, equipment and facilities used during the production stage can involve large, industrial operations – many much larger than any single well pad - that generate noise, light, and other stressors for years to decades, long after stressors associated with the development phase have ceased.

3.1.4 Waste Management

Waste management includes the storage, treatment, re-use, transport, and disposal of liquid wastes (such as flowback and produced water), and solid wastes (such as drilling muds and cuttings). Waste management is an integral part of all stages of oil and gas development and production, although the quantity and characteristics of waste vary among stages. Some of this management occurs at the well pad, but much of it occurs elsewhere (e.g., at underground injection wells and landfills), with the result that waste management can affect a geographic area well beyond the well pad.

Flowback and produced water are sometimes stored on-site in tanks or lined holding ponds, but this latter practice may be changing in favor of transport offsite or recycling. Wastewater production in the Marcellus region has increased significantly in recent years as a result of high-volume hydraulic fracturing technology (Vidic et al. 2013). Because of the large volumes of contaminated wastewater associated with hydraulic fracturing, this part of the water life cycle poses the greatest risk of surface water contamination (Rozell and Reaven 2012). In addition to potential impacts related

> What happens during this stage?
>
> → Storage, possible treatment and re-use, and disposal of oil and gas wastes
>
> How long does this stage take?
>
> → Solid waste products, such as drill cuttings, are stored and removed after drilling. Produced water is generated throughout the lifetime of a well, although the amount of water produced decreases with increasing well age.

to flowback and produced water (see discussion of flowback water above), wastewater management includes impacts related to disposal of chemical precipitants and desalinization wastes from recycling and onsite treatment processes. The treatment of Marcellus wastewater has been associated with increased formation of toxic disinfection by-products, and discharges of insufficiently treated wastewater have been linked to increased levels of salts, naturally occurring radioactive materials, and toxic metals in receiving streams (Vengosh et al. 2014; Warner et al. 2013).

Liquid waste products (e.g., flowback and produced water) from oil and gas operations may be disposed of in underground injection wells, and this disposal practice can be a source of seismic activity. Moderate earthquakes (magnitude 2.0-4.5) associated with injection wells have occurred in areas currently undergoing oil and gas development (e.g. Ohio, Arkansas, and Oklahoma) (National Research Council 2013; Davies et al. 2013; Ellsworth 2013; Jackson et al. 2014).

Although they are acknowledged sources of low-level radiation, solid waste products (e.g. drill cuttings, and sludge) have not been extensively characterized in the literature. Limited evidence has found radionuclides from the uranium and thorium decay series' and elevated beta radiation in samples of non-Appalachian pit sludge (Rich and Crosby 2013).

3.1.5 Post Production and Well Closure

A closed well should be properly secured so that petroleum or salt water cannot escape to the environment. This is commonly accomplished using a cement plug in the wellbore. Few of the newer wells in unconventional Appalachian formation have been closed to date. However, there are many improperly abandoned wells in the Appalachian basin from earlier conventional development that can potentially affect aquifers by acting as pathways for the migration of methane and other VOCs (see discussion of methane migration in the Well Construction section).

> What happens during this stage?
> - → Well closure
> - → Site restoration
>
> How long does it take?
> - → Well closure: Several weeks to position supplies, material, and drilling rig for closure of the well. A week or more to load the well with brine (to stop gas and fluid flow), remove some of the casings, and cement the well.
> - → Site restoration: Indeterminate time, because restoration depends on the lease agreement and whether the site is to be maintained for future development.

3.1.6 Summary of Potential Environmental Stressors

In sum, the various stages of well development, production, and closure have the potential to produce discharges and emissions that may produce ecologic, health, and social impacts. These include:

- *Water quality stressors* that can include spills and wellbore leaks that, if not properly controlled, may affect aquifers and nearby surface waters; discharge of improperly treated wastewaters to surface waters

- *Water usage*, which can stress local aquifers and surface water supplies
- *Air emissions*, which can include a wide range of pollutants emitted from drill sites, producing wells, supporting infrastructure, along roadways serving sites, potentially affecting local and regional air-sheds.
- *Noise, vibration, light, and odor*, which can affect surrounding areas.

In the following sections the Committee reviews the evidence on how these stressors may cause ecologic, health, and social impacts.

3.2 ECOSYSTEMS

This section explains how the stressors described in Section 3.1, and summarized in Table 3 below, might affect aquatic and terrestrial ecosystems in regions undergoing oil and gas development.

3.2.1 Potential Impacts on Aquatic Ecosystems

Impacts Related to Changes in Water Availability

The hydraulic fracturing process uses large amounts of water, on the scale of 1 to 6 million gallons per well. As mentioned in Section 3.1, withdrawal of this water from surface water and freshwater aquifers is typically not an issue in the Appalachian region and comprises only a fraction of the region's industrial water use. In certain circumstances, however, water usage in oil and gas development may affect the structure and function of aquatic ecosystems. Water withdrawals from low-flow or drought-condition streams can decrease available habitat for local species (Brittingham et al. 2014). In contrast, the release of wastewater (treated or untreated) in arid areas may create new habitat or cause changes in the type of available habitat. The only study found relating to water consumption identified no changes in macroinvertebrate or fish communities upstream or downstream of permitted water withdrawal locations for high-volume hydraulic fracturing in Pennsylvania (Shank 2013).

Impacts Related to Changes in Water Quality (Including Sedimentation)

A variety of processes associated with oil and gas development can lead to changes in water quality (see Section 3.1 for a description of potential water contaminants related to oil and gas development). Laboratory studies of the native Pennsylvania mayfly and other model species found Marcellus-formation-produced water to be acutely and chronically toxic and that multiple dilutions were required to decrease toxicity (Stroud Water Research Center 2013). Produced-water toxicity has been attributed to the chemical composition of source water and its overall ion concentration (Stroud Water Research Center 2013) — an observation that aligns with research on conventional oil and gas produced waters (e.g., Fucik 1992, Mount et al. 1992, O'Neil et al. 1992, Fisher et al. 2010). Increases in metals, chloride, and conductivity in local streams have also been associated with non-Appalachian oil and gas development (Burton et al. 2014).

Ecologic impacts related to water quality can occur as a result of planned or accidental releases of wastewater into surrounding streams, although Olmstead and colleagues (2013) did not find any systematic impacts of well pad spills on water quality. Even when the event is planned, as with permitted discharges of treated wastewater, impacts on local ecosystems are still possible. Wastewater discharges in the Marcellus region have been linked to statistically significant changes in stream chemistry and sedimentation (Ferrar et al. 2013b, Olmstead 2013, Warner et al. 2013, Skalak et al. 2013). Changes in stream conditions (e.g. conductivity) caused by oil and gas wastewater discharges have caused lethal and non-lethal responses in fish (Papoulias and Velasco 2013).

Aspects of oil and gas development that alter the existing landscape (e.g., construction of well pads, access roads, pipelines, compressor stations, processing plants) can lead to increased erosion and sedimentation (via stormwater runoff) as well as changes in the pathways and constituents of surface water (Brittingham et al. 2014). Sediment concentrations in Appalachian streams can, in turn, affect native populations of aquatic species such as brook trout (Weltman-Fahs and Taylor 2013; Smith et al. 2012) by decreasing available prey and negatively interacting with stages of the life cycle. Few studies have directly addressed the relationship between oil and gas-related activities, other than wastewater management, and erosion and sedimentation (Williams et al. 2008; McBroom et al. 2012). Some studies have associated increased oil and gas development with increased levels of turbidity (Entrekin et al. 2011) and total suspended solids (Olmstead et al. 2013; Burton et al. 2014) in streams of the Marcellus shale and beyond.

Impacts Related to General Oil and Gas Development

A limited number of studies have examined the relationship between the cumulative stressors of oil and gas development and ecologic impacts. Changes in land-use patterns related to oil and gas development have been associated with negative responses in macroinvertebrate communities (Burton et al. 2014). Additionally, increased density of gas wells has been linked with increased fish (red fin) mortality in non-Appalachian settings (Stearman et al. 2014). Increases in water temperature and barriers to migration and movement (e.g., culverts for new roads or temporary dams for water withdrawals) are key concerns for the Eastern brook trout (Smith et al. 2012, Weltman-Fahs and Taylor 2013) — a species of ecologic and economic importance in the Appalachian region. The Committee did not find studies of the impacts of physical stressors (e.g., light, noise, or naturally occurring radioactive material) on aquatic ecosystems.

3.2.2 Potential Impacts on Terrestrial Ecosystems

Habitat Change, Loss, or Fragmentation

Well pads and other oil and gas facilities and infrastructure (e.g., compressor stations, processing facilities, roads, and pipelines) contribute to the creation of new, emerging patterns of land use and the introduction of multiple stressors, such as noise, light, and chemicals, released through normal operations and accidents. These patterns of land use and other stressors can lead to habitat fragmentation,[5] habitat loss,[6] and other habitat changes. The ecologic impacts of habitat loss and fragmentation range from changes in community structure and composition, to direct mortality (see below).

Well pads in the Appalachian region are typically constructed on 3 to 7 acres of land; roads and other associated infrastructure take an additional 7 to 9 acres (Johnson et al. 2010; Brittingham et al. 2014). Oil and gas infrastructure has been constructed on a variety landscapes, including agricultural land, core forest habitat, and soils with a high risk for erosion and sedimentation (Drohan et al. 2012; PA DCNR, 2014). Erosion-related violations have been reported on a number of oil and gas well sites since 2008, although the number of annual violations has decreased since that time (Rahm and Riha 2014). A report from the Marcellus region predicts that between 700,000 and 1,750,000 acres of Appalachian forest habitat might be converted to gas and oil infrastructure or to edge habitat resulting from such development, with most of the conversion (70%) resulting from pipeline construction (Johnson 2014; Johnson et al. 2010). As a result, regions that were once dominated by deep forest habitats may become fragmented or dominated by edge habitats, leading to changes in light, temperature, moisture, and other components that can directly and indirectly affect surrounding ecosystems (Brittingham et al. 2014; Drohan et al. 2012).

Biotic impacts resulting from habitat loss related to oil and gas development include decreases in secure habitat, disrupted breeding, and changes in community density and structure (Souther et al. 2014). It has been suggested that these impacts increase with increases in land use related to oil and gas development (Thomas et al. 2014). Figure 12 shows landscape changes (habitat loss and fragmentation) that occurred with construction of an ancillary facility, a gas processing plant, and associated pipelines. Habitat fragmentation is well studied in general development scenarios (Souther et al. 2014) and has been associated with changes in wildlife behavior, reduced reproduction success, and the introduction of invasive and competitive species (Brittingham et al. 2014).

Noise and Light

In general, chronic noise and light pollution have been directly related to changes in the behavior (including reproduction rates) and spatial distribution of ecologic communities (Barber et al. 2010; Longcore and Rich 2004). Non-Appalachian studies have identified changes in the density of bird communities and the occupation rate of bird habitat near compressor stations used in oil and gas development (Bayne et al. 2008; Francis et al. 2011). Similar studies of the Marcellus region are forthcoming (Pennsylvania Department of Conservation and Natural Resources (PA DCNR) 2014).

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[5] Breaking up a contiguous area of habitat as a result of land uses such as roads, pipelines, and other pathways.
[6] The direct loss of habitat due to the footprint of well pads and other infrastructure.

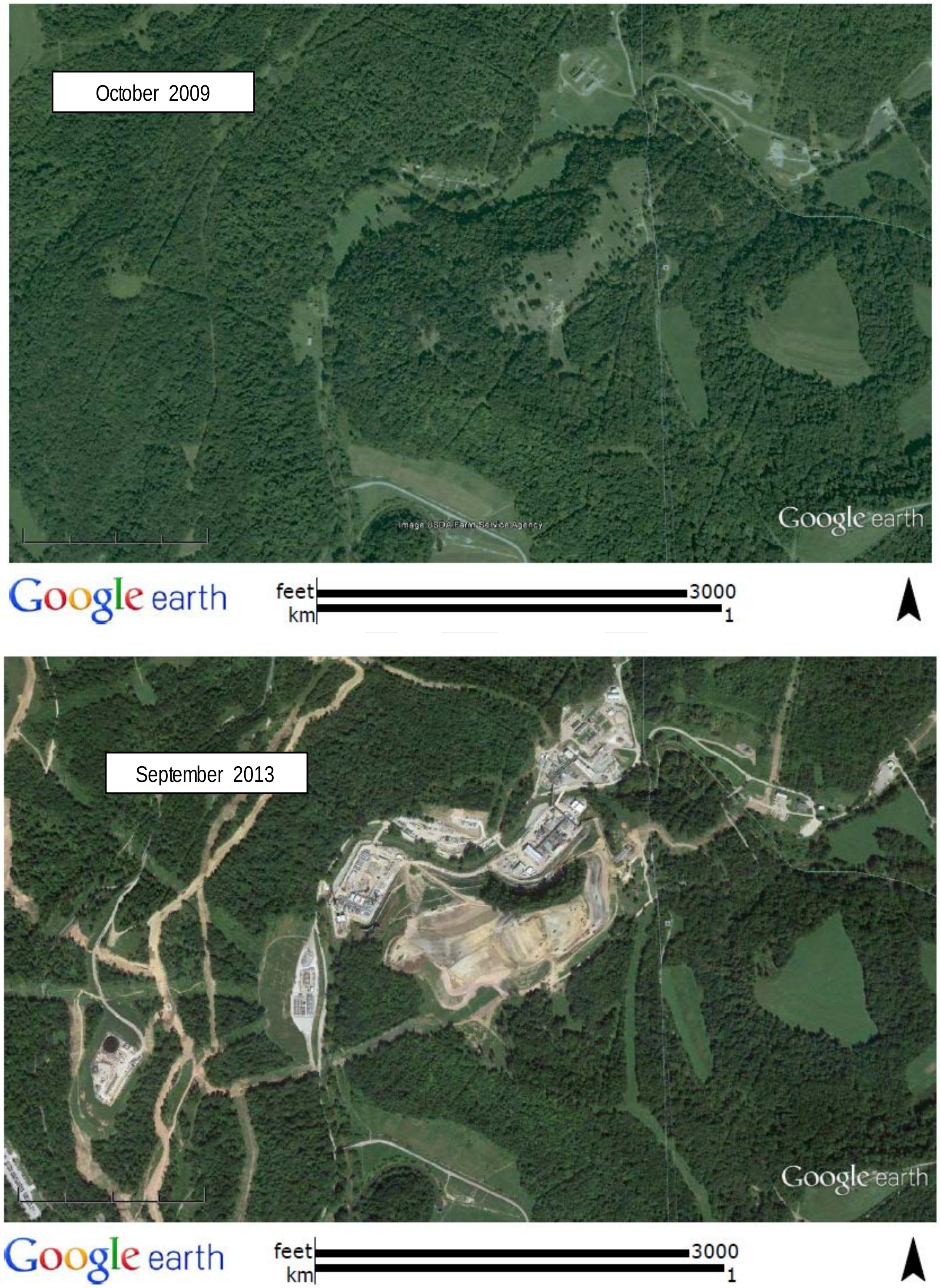

Figure 12. Rapid and dramatic changes in land use resulting from the construction of a large gas processing plant in rural West Virginia.

Change in Competitive Interactions and Introduction of Invasive Species

Heavy equipment and traffic related to oil and gas development can introduce invasive species to Appalachian habitats. The Pennsylvania Department of Conservation and Natural Resources (PA DCNR) (2014)assessed non-native invasive plant species at 18 representative well pads across core forest districts and found 11 species of invasive plant; 14 of the 18 sites had one or more of these invasive species.

Habitat change, loss, and fragmentation can also contribute to changes in the relationship between terrestrial species. Corridors created by well pads, roads, pipelines, and other linear land use can create pathways for predators, parasites, and other organisms that thrive in the newly created edge habitat. Certain species introduced in this fashion have been related to negative competitive impacts on other specialist species (Thomas et al. 2014; oil and gas development related) and can change forest vegetation trajectories (Horsley et al. 2003).

Toxicity and Direct Mortality

Oil and gas development can potentially lead to toxic impacts and mortality in surrounding ecologic communities. Multiple studies have linked air pollution from conventional oil and gas operations to health impacts on beef cattle (Bechtel et al. 2009a; Bechtel et al. 2009b; Bechtel et al. 2009c; Waldner 2008a; Waldner 2008b; Waldner 2008c; Waldner 2008d; Waldner 2008a; Waldner and Clark 2009, Waldner and Stryhn 2008). Although no such studies were found for the Appalachian region, air pollution from oil and gas operations has been measured in heavily forested rural air-sheds in the Marcellus region (Pekney et al. 2014). Conventional oil and gas wastewater (flowback and produced water) has been linked with short term plant mortality and increases in concentrations of brine in soil when spilled or spread in forested land (Adams 2011; Dewalle and Galeone 1990; Auchmoody and Walters 1988). The chemical composition of fracturing wastewater today may vary from the time of these reports. Nonetheless, reports based on prior conditions are relevant for understanding past short-term and potentially long-lasting impacts.

Impacts on Threatened and Endangered Species Habitats

In addition to potential impacts on important and rare habitats, oil and gas development may directly affect populations and the demography of species of high conservation concern. Certain species may suffer direct mortality on roads or well pads, and some species with very small ranges may suffer genetic threats as these ranges are subdivided (Brittingham et al. 2014). Many species of high conservation concern have habitat in the Appalachian region (Johnson 2014); some species that are threatened or endangered at the federal or state level have 100% of their range within the Marcellus or Utica shale regions (Gillen and Kiviat 2012). The Committee did not find studies of direct mortality, community changes, or behavioral changes in these species as a result of oil and gas development. However, the Pennsylvania Department of Conservation and Natural Resources (2014) is sponsoring a study of the impact of well development on timber rattlesnakes (*Crotalus horridus*), a species of conservation concern.

Table 3. Potential stressors of concern for ecosystems in areas with oil and gas development.

Stressor	Concerns
Aquatic Ecosystems	
Changes in water flow patterns and availability	More storm water runoff (e.g., contributing to erosion and sedimentation)
	More consumption of fresh surface water (e.g., base flow decreasing to the point of drying or less groundwater input contributing to water temperature rising)
	Changes to channels and substrates (e.g., cutting, sedimentation, and removal of dead wood)
Changes in water quality	Changes in temperature (affecting all temperature-related processes but of special concern for the survival, growth, and reproduction of cold- and cool-water fishes)
	Introduction of chemicals associated with hydraulic fracturing (e.g., chloride, metals, and other water-soluble ions from shale and deep brine water and organic or inorganic components of fracturing fluids). Aquatic toxicity depends on constituents, concentrations, and exposure.
	Introduction of chemicals associated with other aspects of oil and gas development (e.g., chemicals associated with road and pad maintenance, such as deicing, dust control, and stabilization, and herbicides for road, pad, and right-of-way maintenance)
Increased sedimentation	Well-known direct and indirect effects on macroinvertebrates and fish, resulting from ground disturbance and increased erosion
More light reaching streams	Streamside forest removal can increase water temperature and algal growth
Introduction of more nutrients	Phosphorus and nitrogen in wastewater can fertilize algal and bacterial growth, which in turn can affect macroinvertebrates and fish
Barriers to fish movement	Impacts on fish movements and migrations, access to refugia (locations where conditions allow for the survival of a species or community of species after extirpation in other locations), and the fragmentation of populations
Terrestrial Ecosystems	
Changes in landscape patterns	Impacts on local plant and animal communities, changes in hydrology and soil compaction, erosion, quality of streams, and habitat fragmentation
Changes in soil density, chemistry, and permeability	Toxicity and direct mortality to terrestrial species, erosion, and sedimentation
Noise, light, and human contact	Impacts of roads on animal mortality and changed behavior (e.g., migration patterns)
Terrestrial community structure and composition	Changes to animal communities and composition
Air and water quality; water volume	Toxicity and direct mortality and changes to communities and their composition
Changes in core and edge habitat	Habitat loss, habitat fragmentation, and other biotic community impacts

3.3 Human Health

Oil and gas workers and community members can be exposed to health stressors from oil and gas operations. The potential stressors discussed in Section 3.1, and summarized in Table 4, may affect people's health depending on the magnitude, frequency, and duration of exposure to affected water, air, soil and other environmental media.

3.3.1 Exposure to Potential Health Stressors

Human exposure can be defined as contact between a substance in an environmental medium and the human body at specific points in space over a specified time. Common routes of exposure include inhalation, ingestion, and dermal contact. Through one or more of these routes, workers or members of a local community may be exposed to chemical and physical agents as well as sensory stressors (e.g., odor, light, and noise) associated with unconventional oil and gas operations, as illustrated in Figure 13. The recent increase in oil and gas development in the Appalachian region has been followed by scientific interest in the potential impacts on human health, yet few exposure or health studies have evaluated the levels of exposure and whether they might lead to adverse health effects (Adgate et al. 2014; Goldstein et al. 2014).

Table 4 provides a brief summary of possible exposures that might arise during routine oil and gas operations. Additional exposures might arise during upset conditions; in the extreme, fires and explosions would pose an acute hazard to health to workers and nearby community members. Other upset conditions such as spills might affect air quality or water quality, posing an acute or chronic health concern for workers and others nearby or who are served by an impacted water supply.

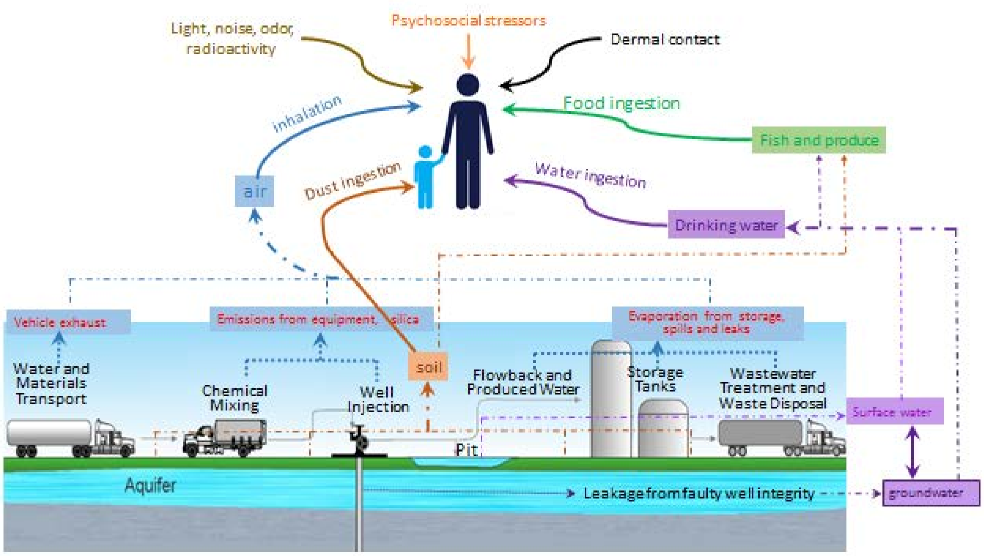

Figure 13. Multi-pathway exposures to chemical agents and physical stressors resulting from oil and gas development. Various pathways and levels of exposure may be associated with the various stages of oil and gas development. Adapted from EPA 2011.

Table 4. Potential exposures to health stressors under routine oil and gas development conditions (versus non-routine, or upset, conditions) for workers and community members living nearby.

Activity	Stressor	Exposure Pathway	Likelihood of Occurrence	
			Workers[b]	Community members
Exploration	Noise, vehicle emissions	Physical exposure, inhalation	High	Depends on proximity and other factors*
Site Preparation	Light, noise	Physical exposure	High	Depends on proximity and other factors*
	VOCs, NOx, PM, air toxics	Inhalation	High	Depends on proximity and other factors*
Drilling	Light, noise, odor	Physical exposure	High	Depends on proximity and other factors[a]
	VOCs, NOx, PM, air toxics	Inhalation	High	Depends on proximity and other factors[a]
	Drilling fluid, dust	Dermal contact	Depends on personal protective equipment (PPE) use	Low
	Chemical release to water	Dermal contact, ingestion	Depends on PPE use	Depends on water source and use
	Chemical release to soil	Dermal contact, incidental ingestion,[c] food ingestion	Depends on PPE use	Depends on bioaccumulation in human food and consumption patterns
Well completion (including hydraulic fracturing)	Light, noise, odor	Physical exposure	High	Depends on proximity and other factors[a]
	Radioactivity	Physical exposure	Depends on rock formation and PPE use	Low
	VOCs, NOx, PM, air toxics	Inhalation	High	Depends on proximity and other factors[a]
	Silica	Inhalation	High; depends on PPE use	Low
	Chemical release to water	Dermal contact, ingestion	Depends on personal protective equipment (PPE) use	Depends on water source and use
	Chemical release to soil	Dermal contact, incidental ingestion[c]	Depends on PPE use	Depends on bioaccumulation in human food and consumption patterns
Production and processing	Light, noise, odor	Physical exposure	High	Depends on proximity and other factors[a]
	Radioactivity	Physical exposure	Depends on rock formation and PPE use	Low
	VOCs, NOx, PM, air toxics	Inhalation	High	Depends on proximity and other factors[a]
	Chemical release to water	Dermal contact, ingestion	Low	Depends on water source and use
	Chemical release to soil	Dermal contact, incidental ingestion	Low	Depends on bioaccumulation in human food and consumption patterns
Waste Management[d]	Drilling muds, drill cuttings, sludge, produced water, and other wastes	Inhalation, dermal contact, incidental ingestion[c]	Depends on PPE use	Depends on proximity and other factors[a]

[a] Meteorological factors (e.g., wind speed and direction, temperature), topography, and other factors can affect the exposures of nearby communities.
b These classifications are approximate and are highly dependent on (1) the use of personal protective equipment, and (2) industry best management practices and health and safety practices at any given site.
[c] Incidental ingestion can occur when contaminated soil adheres to hands or food, and is unintentionally ingested.
[d] Waste management is an integral part of multiple stages of oil and gas development.

3.3.2 Evidence of Health Effects Associated with Oil and Gas Development

Numerous reviews have been published of the potential human health effects of oil and gas development in various regions of the United States (e.g., Maryland Institute for Applied Environmental Health 2014, Penning et al. 2014, Adgate et al. 2014, National Research Council 2014b) and around the world (e.g., Public Health England, 2013). Except for Esswein and colleagues (2013; 2014) most of these reviews focused on the health of people living near oil and gas operations. There have been few, broader population-based (traditional) epidemiologic studies addressing directly the physical or mental health effects of oil and gas development—particularly in the Appalachian region. Most studies involve community-engaged research (which measures community perceptions of risk, self-reported symptoms, and other anecdotal information) or research based on ecological or correlational designs (Steinzor et al. 2012; 2013; Saberi et al. 2014; Perry 2013; SWPA EHP, 2013; Ferrar et al. 2013a).

Future studies must be designed based on an understanding of the full range of exposures that might be related to oil and gas development. Oil and gas activities extend beyond the well pad as truck traffic, compressors, gathering pipelines, processing plants, and other components. There is also variability in the populations exposed. Occupational exposure to chemical, physical, and psychological stressors can happen on the well pad or at any other stage of development and production. Community members may be exposed via air, water, or other physical media. Given the industry's often around-the-clock operations, typical 8-hour occupational threshold limits for worker exposures may not apply. Community exposures - though generally lower than those for workers – may occur over long time periods that involve multiple discrete periods of exposure and may be of special concern for vulnerable populations, including children, pregnant and nursing mothers, the elderly, and individuals with underlying chronic illnesses. In both the worker and community populations, certain age groups may be more vulnerable than others.

Exposures related to the extraction of oil and gas can involve a combination of potential health stressors. The effects of individual stressors are often not well understood, and even less is known about their cumulative effects. The need for efficient methods to evaluate the biologic significance of exposure to multiple stressors has been reviewed extensively (e.g., Sexton 2012, Goldstein et al. 2014). But at this time, insufficient data are available in most instances to quantify exposures to multiple stressors and to predict health effects from these exposures. This problem is exacerbated in the case of oil and gas development where the problem of missing chemical-mixture toxicity data is compounded by the small number of studies that include reliable measurements of worker and community exposure collected at locations and over time periods relevant to understanding potential risks to health.

A significant amount of oil and gas development is occurring in sparsely populated areas, limiting the possible sample size and statistical power of epidemiological studies to detect health effects. On the other hand, in some areas outside the Appalachian region, development is occurring in highly populated regions (e.g. Dallas-Fort Worth) making it difficult to parse the contributions of other pollution sources. Additionally, exposure metrics have not been well defined. Oil and gas technologies vary from place to place depending on geology, and other factors and processes - including safety measures - have changed over time, making it difficult to generalize across regions, categorize exposures, or predict health consequences in the context of an epidemiologic study.

Oil and Gas Workers

Chemical Hazards. Many community concerns about oil and gas operations focus on chemical exposures. Oil and gas workers actively use these chemicals or work in proximity to them, and consequently face the potential for higher exposures than people living nearby. In addition, they face more physical hazards that can contribute to morbidity and mortality. Only a few reliable studies have been published about unconventional gas workers and the rapid pace of changing technology makes occupational studies challenging to conduct or interpret. Areas of particular safety concern include greatly increased traffic, use of substantial volumes of liquids at operationally high pressure, fracturing fluid additives, particulate silica; and the need for intermittent human activity in hazardous operations.

A unique concern for unconventional gas workers, distinct from the rest of the oil and gas industry, is the substantial use of fine crystalline silica as a suspended proppant in the fracturing fluid. Workers can be exposed to this silica during local transport and especially during mixing or blending into the fracturing fluid (See Figure 14).

Figure 14. Generation of silica dust in a hydraulic fracturing operation. (Source: http://blogs.cdc.gov/niosh-science-blog/2012/05/23/silica-fracking/).

The National Institute of Occupational Safety and Health (NIOSH) conducted exposure studies demonstrating the presence of a respiratory hazard from silica for workers in five states, including Pennsylvania (Esswein et al. 2013). The data reveal that the potential for overexposure does exist in specific operations and needs to be mitigated by best practice. Respiratory exposure to crystalline silica is a cause of silicosis (a fibrotic lung disease), increased risk of autoimmune disorder, susceptibility to infection such as tuberculosis, of kidney disease, and lung cancer (Esswein et al. 2013). Silicosis has a substantial latency between the initial exposure and the onset of detectable disease processes, meaning it will take time and determination to understand the risk to oil and gas workers. Hazard reduction engineering and process protections are being developed by NIOSH and others, which could reduce workplace exposures and prevent health risks such as silicosis if used appropriately.

Diesel exhaust affects workers as well as communities. Diesel exhaust is released from trucks (while transporting equipment, water, chemicals, and waste to or from the well site), power generators at the work site, and other engines on and off the well pad associated with the extraction and production of oil and gas. Diesel exhaust mixes with other PM and with gaseous pollutants such as NO_x and CO. These air pollutants have well-known health effects, including increased mortality from respiratory and cardiac causes as well as from all causes combined, and increased incidence of pulmonary conditions, such as asthma, respiratory infections and other ailments. Diesel exhaust from older engines has also been classified as a known human carcinogen by the International Agency on Research on Cancer. Emissions of PM, NO_x and other toxic components from diesel exhaust are on downward trends as newer engines (post 2007 and 2010 model years) are introduced into the truck fleet.

Rates of COPD also increase with increased exposure to air pollution, and workers may be especially at risk due to concentrated exposure opportunities. Diesel exhaust exposure (measured as respirable particulates) at unconventional gas extraction sites can exceed regulatory standards; NIOSH found 20% of their samples exceeded 20 ug/m^3, the regulatory standard in California (Esswein et al. 2014).

Low-level ionizing radiation is known to be present both in flowback water and especially in returned solids such as drill cuttings and sludge. Total beta radiation activity can substantially exceed regulatory guidelines for conventional handling (Rich and Crosby 2013). This potential impact of these exposures on the well-being of communities has been discussed in the media and elsewhere, but there has been scant discussion concerning workers or assessment of exposures associated with specific operations. Workers at sanitary landfills may also be exposed to radioactive solid waste from oil and gas operations because of state-mandated requirements to accept shipments of large quantities of solid waste.

Workers may be exposed to benzene and other VOCs at the wellhead of any oil and gas operation; this exposure is not unique to unconventional gas wells. In unconventional gas operations, benzene from deep underground sources can also accompany the production of methane or arrive along with substantial quantities of initial flowback water (Esswein et al. 2014). Previous studies have found elevated worker exposures to benzene during flowback operations, but specific health outcomes related to such exposures at well sites have not been characterized. Bloomdahl et al. (2014) used mathematical models to predict worker exposure to 12 VOCs evaporating from flowback water stored in an open reservoir under hypothetical conditions. However, actual worker exposure would be determined not only by industrial practice (e.g., the way flowback water is stored and the effectiveness of personal protection equipment, the length and frequency of work shifts) but also by meteorological conditions affecting the evaporation and dispersion of the VOCs. In the NIOSH investigation (Esswein et al. 2014), on-site eight-hour time-weighted average measurements of benzene concentrations in workers' personal-breathing-zones during the flowback period showed concentrations above NIOSH's recommended exposure limit (REL) of 0.1 ppm time-weighted average but below OSHA's permissible exposure limits. Other VOCs measured in the study were well-below their permissible exposure limits. Certain task-based activities (e.g., those of flowback technicians) were associated with increased benzene inhalation exposure based on 15-minute time-weighted average personal-breathing-zone measures and concentrations of certain benzene metabolites in worker urine (Esswein et al. 2014) No data on the magnitude or frequency of occupational exposure to hydrogen sulfide are available; many companies require use of alarmed personal hydrogen sulfide monitors to prevent fatalities (Adgate et al. 2014). Similarly, quantitative data are not available in the published literature on occupational exposure to diesel exhaust particles, drilling and fracturing chemicals, produced water, or noise from oil and gas activities.

Physical Hazards. Oil and gas workers are at risk for a range of possible injuries, including falls; lifting injuries; burns; and contact with, being struck-by, or caught-on equipment. Injuries and fatalities can also result from vehicular accidents, and such accidents have received more attention than other sources of injury in the recent literature. The rate of vehicular fatalities in the general oil and gas industry is about eight times greater than that of other occupations (Adgate et al. 2014; Retzer et al. 2013). About 70% of fatalities in the private mining sector are caused by oil and gas industry operations (Bureau of Labor Statistics US Department of Labor 2014), and truck accidents caused 49% of general oil and gas worker fatalities in 2012, representing a far greater rate of worker vehicular mortality than in other industries (Retzer et al. 2013). Unconventional gas operations can thus be expected to feature a high rate of worker motor vehicle injuries and deaths (National Research Council 2014b; Retzer et al. 2013). In contrast with these vehicular and fatality rates, however, the rate of non-fatal injuries is reported to be lower than in the construction industry (Bureau of Labor Statistics US Department of Labor 2014).

Physical hazards are also associated with gases. Direct reading measures indicated that hydrocarbon vapors accompanying flowback fluids can be as high as 40% of the lower explosion limit (Esswein et al. 2014). Explosions and fires are an important worker hazard and have occurred at both conventional and unconventional gas sites, with attendant consequences, including death.

Sensory Hazards. Noise is well known to be a hazard in the oil and gas industry. Compressors have been measured to produce a continuous 105 dBA (i.e., decibels with A-weighting, which is believed to best approximate human response to sound; New York State Department of Environmental Conservation). This sound level can produce permanent hearing loss. However, industry is trending toward less noisy compressors. Shale shakers, drilling operations, flares, and other operations are also often very noisy. Workers are usually closer to the source of noise than are residential neighbors, although workers may be better able to protect themselves. In occupational settings (not oil and gas operations specifically), noise exposure has been linked with increased rates of myocardial infarction (Basner et al. 2014) and hypertension (Tomei et al. 2010). Depending on the use and effectiveness of hearing protection equipment, it is likely but not known that these problems will pertain to workers at oil and gas sites, too.

Work Schedules and Shift Work. Operations during some stages of oil and gas development occur 24 hours a day, necessitating shift work. No studies characterize the nature and variation of the shift work practices and potential health outcomes among workers.

Communities Living Near Oil & Gas Operations

Chemical Hazards. Few studies have characterized the emission and distribution of pollutants from the well pads and diesel traffic associated with oil and gas operations. However, some source emissions data have been used to predict exposure. For example, a recent study measured chemical concentrations in waste streams from oil and gas development in the Marcellus formation to make inferences about exposure via water ingestion (Ziemkiewicz et al. 2014). In addition, ambient air quality may be monitored for assessing compliance with ambient air standards. McKenzie et al. (2012) used such air quality measurements at well-pad perimeters to assess human exposure. Data from these and other recent studies, often measured as 24-hour-average concentrations, do not adequately characterize the intensity, frequency, or duration of actual human exposures, because they may not capture the spatial or temporal variability in exposure within and across communities (Brown et al. 2014). Such variability in exposure can be important in judging whether the exposure might be harmful. These exposure data also might not distinguish the influence of oil and gas operations from other sources of chemicals detected in air (such as those from wood smoke, farm machinery, or chemical applications on farms.).

Some of the chemicals emitted during oil and gas operations (e.g., diesel exhaust, and benzene) have well-known adverse health effects and thus have the potential to affect the health of nearby community members. However, well-conducted studies specifically linking oil and gas-related exposures to adverse outcomes do not exist, and their absence is an important knowledge gap. Also, there has been little or no attention to the potential combined effects of exposure to complex mixtures of hazardous compounds (Goldstein et al 2014).

Unconventional oil and gas development has been tentatively linked to adverse reproductive outcomes in one epidemiologic study (McKenzie et al. 2014). McKenzie et al. (2014) concluded that mothers who lived in “high-risk” locations were more likely to give birth to a child with congenital heart defects or neural-tube defect than mothers in “low-risk” locations. However, as these authors acknowledge, the study was subject to important sources of uncertainty, such as the exposure metric, proximity to wells, which was not specific to any particular health stressor. It would therefore be inappropriate to rely on this study to reach definitive conclusions about adverse health outcomes related to oil and gas development, but it should be considered when formulating hypotheses for future study.

Physical Hazards. Increased industrial traffic in residential areas may also decrease access to outdoor recreational activities for residents who live near affected roads (Ortega et al. 2010). This is potentially important because of the known beneficial relationship between exercise and reduced mortality (Lee et al. 2014). Rural areas of Appalachia do not necessarily have preexisting infrastructure such as sidewalks or wide road shoulders. Furthermore, increased traffic associated with drilling operations may increase risk of traumatic road or pedestrian injuries (Witter et al. 2013; Maryland Institute for Applied Environmental Health 2014). An increase in heavy-duty truck accidents has been reported in Pennsylvania counties with substantial unconventional gas activity, and unconventional gas operations in Texas have been associated with a 40% increases in motor vehicle fatalities in affected counties (Maryland Institute for Applied Environmental Health 2014).

Sensory Hazards. Residents of the Appalachian region have expressed concern about noise and light related to drilling compressors, increased truck traffic, and the process of hydraulic fracturing. Noise and bright light can affect sleep quality and cause sleep disturbances (Passchier-Vermeer and Passchier 2000). Artificial lighting from operations can intrude into homes and may be especially intense during flaring operations. Flaring operations can also be a source of disruptive noise. Heavy truck traffic is a source of noise and vibration when routed close to dwellings. Compressor stations are generally further away but can make continuous noise and vibration that can intrude into homes. Near neighbors of compressor stations or heavy truck traffic roads may express concern about perceived vibration and noise. A study from West Virginia reported that homes within 2,500 feet of a compressor station had 52 to56 dBA noise levels inside the home during night-time hours. For homes near operations, sound levels were 10 to14 dBA higher than in control homes (Maryland Institute for Applied Environmental Health 2014). The dBA scale is logarithmic; an increase of 3 dBA represents an approximate doubling of noise levels; an increase of 10 dBA represents an increase of approximately an order of magnitude. The U.S. Environmental Protection Agency recommends that indoor residential noise levels should be less than 45 dBA, even during active periods.

Studies in urban residential areas suggest that increased traffic noise is linked to cardiovascular disease (Babisch 2011). Other potential health effects include stroke and hypertension (Basner et al. 2014). Lighting is required around the clock at some stages of oil and gas development and continuous well pad operations. Artificial light exposure can affect processes related to circadian rhythm, such as sleeping patterns and energy metabolism. Social changes associated with the growth and population influx caused by the unconventional gas industry bring both opportunity and some predictable patterns of disease and injury (Adgate et al. 2014). Few studies have measured the prevalence of perceived stress in communities affected by unconventional oil and gas development, and no published studies have attempted to measure the relationship between health and clinically identified stress in such communities. In other settings, psychological stress has been associated with cardiovascular disease (Cohen et al. 2007; Dimsdale 2008), immune system suppression (Segerstrom and Miller 2004), cellular changes (e.g., telomere shortening) (Epel et al. 2004), altered childhood development (e.g., changes in hormone and immune pathways) (Wright et al. 2005; Wright et al. 2002; Wright et al. 1998), and depression (Cohen et al. 2007). The psycho-social effects of unconventional oil and gas development as related to communities are discussed in Section 3.4.

Self-Reported Health Concerns. Several groups have surveyed health concerns of those who live near unconventional gas activities. Although these surveys did not imply causal relationships, they did identify issues, including the importance of secondary and psychological stressors related to unconventional gas extraction, that will need to be taken into account in any future research agenda. The biologic plausibility of these reported symptoms clearly depends on potential exposure levels, but measures are scant, and studies to date have been based on designs that limited the ability to draw firm conclusions. They have value as hypothesis-generating studies.

Populations living near unconventional gas operations (including compressors) most commonly report symptoms that can be categorized as dermatologic, neurologic (including sensory and sleep), psychological or emotional, or respiratory. Symptom surveys have been conducted with convenience samples (i.e., readily available samples rather than ones collected during a systematically designed sampling program, such as random sampling) from several regions (Ferrar et al. 2013a; McDermott-Levy et al. 2013; Steinzor et al. 2013).

In a survey of 492 persons in 180 randomly selected households in Washington County, Pennsylvania, self-reported skin, respiratory and other symptoms as well as diagnoses such as hypertension and some respiratory diseases were found to increase with decreasing distance from the nearest gas well (Rabinowitz and Slizovskiy 2014). Other potential outcomes of concern, such as adverse reproductive and developmental effects, were not surveyed.

Less formal citizen surveys have suggested that odors may be a trigger for some symptoms, although systematic evidence is limited (Steinzor et al. 2012; Steinzor et al. 2013). There are a number of potential odor sources in unconventional gas operations, ranging from diesel exhaust to escaped volatile compounds at the well pad. Holding ponds, which are less common in newer operations but still present in some operations, contain chemical mixtures that have their own odors and that can also be a nutrient source for microorganisms that can generate very offensive odors. Aerators in ponds can improve oxygenation and microbial odor characteristics, but may also distribute the odors. A recent study from the Barnett shale region (in Texas) found hydrogen sulfide levels above odor detection thresholds at the operational fence line (Eapi et al. 2014).

Neuropsychological factors may also contribute to expressed symptoms as well as real physical health outcomes. Ferrar et al. (2013a) reported that the belief that physical health had been affected was associated the with the report of stress, and with loss of trust in industry representatives and government officials, consistent with previous research relating lack of trust leading to amplified risk perception (Slovic 1987).

Epidemiological Studies. Exposure assessment to evaluate health risks for people living near oil and gas operations have been conducted in only a handful of studies and with inadequate exposure metrics. A human health risk assessment in Garfield County, Colorado, for example, estimated subchronic non-cancer hazard indices using proximity to well pads (McKenzie et al. 2012). In a study of childhood cancer incidence in Pennsylvania, Fryzek et al. (2013) compared the incidence of various types of cancer in children living in Pennsylvania counties before and after drilling different subcategories of wells (i.e., all gas wells, horizontal wells, horizontal gas wells, Marcellus shale wells). Although the specific methods used to quantify exposure differed between them, two studies used mothers' residential proximity to natural gas development as an exposure proxy to examine the impact on birth outcomes in rural Colorado (McKenzie et al. 2014) and Pennsylvania (Hill 2013; not yet published in a peer-reviewed journal). It is unclear what is encompassed in measures such as distance, and the potential for exposure misclassification is great. McKenzie et al. (2014) describes some of the limitations of their work; for example, residential proximity to, or distance from, oil and gas wells does not necessarily account for factors such as the stage of well development and production, the duration and severity of exposure, the specific technology being used, and other possible sources of the chemicals being monitored or to account for meteorological factors. Proximity may also reflect, in addition to chemical exposures, noise, light, traffic, and other factors that increase with proximity to the well site. In addition, Fryzek et al. (2013) did not account for the expected latency period of childhood cancers, further limiting the utility of the study (Goldstein and Malone 2013).

In rural areas, people living near oil and gas operations may also be concerned about reduced crop yields as well as impact on farm animals and pets that they attribute to the gas operations (Ferrar et al. 2013a; Bamberger and Oswald 2012; 2014). Studies have investigated possible links between oil and gas operations and effects on domestic animals (Bechtel et al. 2009a; Bechtel et al. 2009b; Bechtel et al. 2009c; Waldner 2008a; Waldner 2008b; Waldner 2008c; Waldner 2008d; Waldner 2009; Waldner and Clark 2009; Waldner and Stryhn 2008).

3.4 PEOPLE AND COMMUNITIES

Potentially significant social and psychosocial impacts can be expected to result from large-scale unconventional oil and gas development. Such effects result in large part from the scale and intensity of development activity in some locations and resulting changes in labor force demand, worker in-migration, local population change, demands on infrastructure and services, and changes in the character of both social and biophysical landscapes. At the same time there are substantial uncertainties about the likelihood and extent of some impacts, given the highly varied contexts in which oil and gas development occurs (Jacquet et al. 2014) (Table 5).

The high volume of truck and heavy equipment traffic required to support drilling and well completion operations appears across nearly all situations to result in increased concerns and dissatisfaction among local residents and public officials with traffic flows and congestion, damage to roads and highways, increased accident rates, and reduced traffic safety (Brasier et al. 2011; Ladd 2013; Ladd 2014; Perry 2012; Schafft et al. 2014; Weigle 2011, Muehlenbachs and Krupnick 2013). Also, in more rural and remote settings that experience fairly extensive drilling and extraction activity, a variety of effects associated with workforce in-migration and resulting population growth pressures can be anticipated, at least in the near term, when drilling, well completion, and pipeline construction activities are most intensive (Jacquet et al. 2014; Murdock and Leistritz 1979). For example, areas experiencing major oil and gas development often undergo substantial expansion of demand for worker housing, leading to problems with housing shortages, increased reliance on temporary and in some cases substandard housing, rising costs for rental housing, and increased homelessness (Brasier et al. 2011; Perry 2012; Schafft et al. 2014; Williamson and Kolb 2011).

Table 5. Potential stressors and concerns for social systems in areas with oil and gas development

Stressor	Concerns
Change in population from workforce in-migration	Housing shortfalls and housing cost increases
	Increased demand on public infrastructure, utilities, and school systems
	Increased demand on emergency response and medical services
	Increased demand on social and mental health service providers
	Negative fiscal impacts on local units of government
	Increased crime and increased fear of crime
	Reduced interpersonal familiarity and social integration
	Potential for tensions, conflicts, and distrust between established and newcomer populations
Increased truck and other heavy equipment traffic	Damage to roads and highways, with resulting fiscal impacts on local governments
	Increased problems and concerns involving traffic safety
	Increased traffic congestion and travel delays
	Public dissatisfaction over disturbances involving increased noise, dust, and traffic congestion
Differing public views about the "opportunities" and "threats" resulting from resource development	Increased potential for interpersonal disagreements, tensions, social divisions, and community conflict
Development-induced environmental disturbances and changes to socially valued environments and landscapes	Reduced levels of satisfaction among area residents with place and community
Potential for environmental contamination	Heightened levels of risk perception and associated psychosocial stress effects
	Reduced levels of trust and confidence in agencies and organizations responsible for protecting environmental quality and human health and safety
	Increased potential for corrosive community conflicts
	Increased potential for economic and social stigmatization of local communities

Growth-induced demands on a variety of public facilities and services can also be problematic, especially during the earlier phases of development, when a rapid increase in primarily temporary workers can exceed the existing capacities of rural utility systems, school systems, law enforcement, emergency response services, medical and mental health services, and social welfare systems (BBC Research and Consulting 2013; Brasier et al. 2011; Jacquet 2014; Maryland Institute for Applied Environmental Health 2014; Perry 2013; Theodori et al. 2009; Weber et al. 2014; Weigle 2011). Although local governments and service providers may after some period of time adapt to and address the demands associated with rapid growth pressures, the ability to do so can be limited at first, and possibly over the longer term as well, if taxation and revenue allocation structures fail to provide an adequate flow of funds to the affected communities (BBC Research and Consulting 2013; Jacquet 2014; Jacquet et al. 2014).

Large-scale development activities can strain the social fabric of affected communities. Where such development generates rapid growth, there is considerable potential for reduced interpersonal familiarity at the local level, accompanied by changes in social interaction patterns and reduced levels of social integration and civic engagement (BBC Research and Consulting 2013; Freudenburg 1986; Sampson 1991; Smith et al. 2002; Wynveen 2011). These changes are also likely to contribute to lowered levels of interpersonal trust, manifested in part by increased fear of crime (BBC Research and Consulting 2013; Brasier et al. 2011; Ladd 2013; Theodori et al. 2009). Tensions and conflicts between "oldtimer" and "newcomer" populations may also arise, exacerbating the erosion of trust among local residents (BBC Research and Consulting 2013; Brasier et al. 2011; Perry 2012; Wynveen 2011).

Tensions and conflicts among residents who hold highly divergent views about the consequences of resource development can also contribute to strained local social relations (Gramling and Freudenburg 1992; Jacquet 2014; Ladd 2014; Perry 2012; 2013; Theodori et al. 2009). In the case of unconventional oil and gas development occurring in areas where both land and oil and gas resources are owned by the same private landowners (as opposed to split estates, where surface and sub-surface rights are owned by separate entities), increased potential for wealth creation can lead to highly varied outcomes in how residents experience the "opportunities" and "threats" associated with the development as well as to quite different views about the development's acceptability (Brasier et al. 2011; Perry 2012; 2013). Some residents are likely to experience significant economic benefits from leasing their land for development, access to new and higher-paying jobs, or the expansion of local businesses or other income-generating activities (Brasier et al. 2011). Others may perceive benefits linked to a broader range of opportunities associated with increased tax revenues or may simply consider resource extraction to be consistent with their values and views about growth, development, and "progress" (Brasier et al. 2011; Ladd, 2013, 2014; Schafft et al. 2013). At the same time, some businesses may be negatively affected by wage inflation and increased difficulties in attracting or retaining workers (BBC Research and Consulting 2013; Brasier et al. 2011). In addition, some area residents are likely to be concerned about and dissatisfied with what they consider to be unacceptable alterations to the biophysical environment, local landscapes, valued social and cultural conditions, or family and community traditions (Perry 2012; 2013; Weigle 2011).

Dissatisfaction, tensions, and conflicts may also become problematic where concerns about potential environmental contamination from drilling and production activities lead to widespread perceptions of risks to human health and safety and to distrust of individuals and organizations charged with protecting environmental quality or community health and welfare (Boudet et al. 2014; Brasier et al. 2011; Jacquet 2014; Kroll-Smith and Couch 1989; Ladd 2013; Perry 2012; Slovic et al. 1991; Stedman et al. 2012; Theodori et al. 2013). Effects such as these can lead to increased stress at the individual level and to corrosive social relations at the collective level (Freudenburg 1997; Freudenburg and Jones 1991; Jacquet 2014; Kroll-Smith and Couch 1989; Ladd 2014; Perry 2012; Picou et al. 2004). Stigmatization of local residents and of entire local communities can occur when others in the area characterize them as undesirable or potentially "contaminated" in terms of environmental or social conditions (Edelstein 1988; Kroll-Smith and Couch 1989; Muehlenbachs et al. 2013; Perry 2013; Weigle 2011; Wulfhorst 2000).

Although the literature addressing the social effects of unconventional oil and gas development has expanded considerably in recent years, many of the studies conducted to date have been somewhat limited with respect to topics such as the range of development contexts considered or the number of interviews conducted, and none has provided a longitudinal analysis of change patterns across significant periods of time. Most studies have focused on the subjective perceptions and attitudes of residents and officials in affected areas, with little evidence of an extension of research to include the examination of more "objective" data, addressing topics such as crime rates, changes in social service agency caseloads, and rates of mental health treatment.

In addition, the thresholds at which an interaction of development intensity, remote location, and rural conditions may combine to produce difficult-to-manage effects of boom growth have not been determined. Although earlier research focused on other energy development contexts has suggested that many adverse social effects may be short lived and that adaptation and improved well-being can occur over the longer term (Brown et al. 2005; Smith et al. 2002), the nature and timing of such adaptations have not been clearly established across various areas affected by unconventional oil and gas development. Because no studies have been conducted assessing the longer-term consequences of unconventional oil and gas development, it is not known whether the patterns of declining economic opportunity and well-being associated with many forms of "resource dependency" will also be associated with these newer forms of extraction, especially given the unique spatial and temporal patterns that characterize them (Jacquet et al. 2014).

An additional source of uncertainty relates to the fact that virtually all of the literature addressing the social consequences of unconventional oil and gas development has addressed impacts only at aggregated levels of analysis, typically focusing on changes and stresses that may be observed at the community or county levels. Such approaches fail to address the likelihood that both positive and negative impacts will be unequally distributed and differentially experienced at different spatial scales and among various groups and types of residents — for example, younger versus older persons, newcomers versus long-term residents, women versus men, lower-income versus higher-income populations, those who own undeveloped land versus those who do not, and renters versus homeowners (Beckley 1998; Branch et al. 1984). Further assessment and more refined research designs are needed to address these types of distributive impact issues and more clearly determine which subsets of local residents will tend to experience changes that make them relative "winners" or "losers" with respect to the benefits and costs of oil and gas development.

Finally, the relationships between social and psychosocial effects and human health consequences are not yet clearly understood or carefully documented. Although it seems clear that the alteration of valued biophysical and social landscapes, reduced interpersonal familiarity and social engagement, increased risk perception, loss of trust, increased interpersonal conflict, corrosive communitywide conflicts, and other social effects as outlined above can lead to individual-level stress effects and perhaps to "collective trauma" (Jacquet 2014; Perry 2013), concrete evidence of associated adverse effects on human mental or physical health remains unavailable. Although the potential social and psychosocial effects of unconventional oil and gas development are important in their own right and merit careful assessment, additional research is needed to track their possible implications for human health.

4. NEXT STEPS

There continues to be debate about the potential impacts of 21st century oil and gas development in the peer-reviewed scientific literature, in governmental and nongovernmental reports, in the communities, and in the press. Although more peer-reviewed studies have been published in recent months now that the rapid increase in gas development has been underway in Appalachia for several years, the Committee finds that more research is needed to understand what types of impacts might have occurred in the past, might be ongoing, or might develop in the future. Data gaps plague our understanding of even the most commonly discussed potential impacts, as discussed in Section 3 of this report. Given this paucity of data, it is even more challenging to look ahead to the information needed to answer future questions about cumulative impacts on people and communities near well pads and ancillary facilities, on workers during all stages of oil and gas development, and on the environment and ecologic systems of the Appalachian region.

Many agree about the need for more study of potential impacts and have formulated research recommendations. Table 6 summarizes recent recommendations, assembled from peer-reviewed scientific literature and reports from non-governmental research organizations, industry, and governmental agencies. This summary captures the primary essence of recommendations; more detailed information can be found in the underlying publications. Some data collection and research alternatives appear in the literature more frequently than others. The recommendations that appear most frequently involve data collection to support research, notably baseline air and water quality data representative of conditions in the absence of oil and gas operations, and data needed to understand exposure to oil and gas-related stressors for oil and gas workers, nearby community members, and ecologic systems.

The Committee believes that these recommendations provide very useful input to its research planning deliberations. The Committee's Research Plan – to be released in mid-2015 – will address a wide range of potential environmental, ecologic, human health, and social impacts that today's oil and gas development might have at the local and regional level.

Table 6. Summary of recent research recommendations from the peer-reviewed scientific literature and reports from industry, non-governmental research organizations, and governmental agencies

ENVIRONMENT
Air, Water, and Soil Quality
Characterize baseline air and water quality and monitor over well lifetime[1,2,3,4,5,6,8,9,11,15,18,19,22]
Determine fate and transport of fracturing-related fluids in the subsurface [2,6,15,18,22]
Assess cumulative impacts on air, water, and soil over well lifetime [3,4,9,19,22]
Establish local and regional emissions inventories[1,3,15]
Characterize and model air and water quality changes during each stage of development (e.g., drilling, fracturing, etc.)[3,5,15]
Determine the likelihood of aquifer contamination due to subsurface migration[1,6,22]
Determine the severity of erosion and siltation resulting from oil and gas development [9,22]
Identify signature chemicals associated with oil and gas development for water quality monitoring[1,15]
Water Quantity
Predict and measure the quantity and impacts of water withdrawal, particularly in arid or low-flow regions[1,4,9,11,15]
Develop new technologies to reduce water use[1,15,22]
Wellbore Integrity
Assess wellbore integrity throughout well lifetime[1,15,21]
Hydraulic Fracturing
Determine the general probability of well re-fracturing [1,2,4,15]
Test fracturing fluid and produced water for hazardous physical and chemical constituents [2,6,22]
Waste Management
Determine the physical (e.g., naturally occurring radioactive materials) and chemical (e.g., heavy metals, toxic components) characteristics of drilling and hydraulic fracturing wastewater (e.g., flowback and produced water)[1,2,6,8,11,22]
Determine the safest and most effective methods to manage and treat wastewater, particularly produced water[2,6,18,22]
Determine chemical and radiologic composition of solid wastes (e.g., cuttings)[11,22]
Assess the environmental risks resulting from accidental releases of wastewater [18]
Accidental Releases and Upset Conditions
Create inventory of orphaned/abandoned wells[3] and investigate the role of such wells in the migration of gas and fluid [8,18,21]
Study the occurrence and severity of wastewater spills [2,20,22]
Induced Seismicity
Assess the potential for and mitigation of induced seismicity from fracturing fluid disposal via deep injection wells[1,11,15,17]
Test for preexisting fault systems at deepwater injection sites; associate various factors (e.g., temperature, pressure) with the size and incidence of seismic events[1,17]
ECOLOGY
Spatial analysis of habitat loss/ fragmentation[4,9,11,13]
Model and assess impacts on vulnerable or sensitive species and habitats[4,9,15]
Impacts of aquifer contamination (e.g., gas, brine) on terrestrial and aquatic species[4,9,11]
Investigate the spread of invasive species[4,9]
Determine cumulative impacts on aquatic and terrestrial ecosystems[9,15]
Determine ecological thresholds to minimize impacts (e.g., well count, forest loss, toxicity)[4,22]
Baseline data on aquatic and terrestrial habitats[4,22]
Study habitat impacts of noise and light pollution[19]
Determine effectiveness of ecosystem protection and conservation strategies[2]
Assess the extent of partial and full well pad reclamation[19]

(table continued on next page)

Table 6. Summary of recent research recommendations from the peer-reviewed scientific literature and reports from industry, non-governmental research organizations, and governmental agencies (continued)

WORKER HEALTH
Characterize worker exposure to air and water toxics (e.g., diesel exhaust, fracturing chemicals, silica, H_2S), noise, and naturally occurring radioactive materials [5,10,12,15]
Disease surveillance in defined worker population[5,12]
Complete targeted and non-targeted biomonitoring in a defined worker population[14]
Evaluate the effectiveness of industry efforts to increase safety and limit occupational exposures[11,12]
Assess the extent of workplace injury under-reporting[12]
INDIVIDUAL COMMUNITY MEMBER HEALTH
Determine magnitude and duration of exposure to stressors in air, water, and other environmental media [2,5,11,15]
Assess the relationship between exposures and the spatial and temporal distribution of health outcomes in areas experiencing oil and gas development [8,10,14]
Perform environmental epidemiology studies to evaluate whether oil and gas-related exposures are associated with adverse health outcomes (e.g. cardiovascular disease [air], birth defects [groundwater])[6,8,15]
Characterize sensory (odor, noise, light) stressors and link to health effects[5,6]
Conduct biomonitoring of a representative population for stressors associated with oil and gas development [14]
Conduct health impact assessments of oil and gas development, particularly in rural areas with limited baseline disease prevalence data[11]
TOXICOLOGY
Conduct toxicological studies, coupled with exposure studies, with particular attention paid to ongoing and likely future exposures to mixtures of stressors and their toxicological modes of action[2,6]
Accelerate the toxicological evaluation of chemical and physical stressors associated with hydraulic fracturing[6] (e.g., toxicological components of the U.S. Environmental Protection Agency study that is underway to understand the potential impact of hydraulic fracturing for oil on drinking water resources (http://www2.epa.gov/hfstudy)[2]
PEOPLE AND COMMUNITIES
Develop regional predictions of long-term energy development[1,5,7,15]
Seek community input in the design and completion of ecologic,, human health, and social-psychological research[5,6,8,22]
Examine the relationship between social-psychological changes (e.g., stress) and health effects[5,7,11]
Identify the extent and severity of traffic related impacts[7,11,16]
Document legacy economic and social impacts[7,11,13]
Monitor the impact of oil and gas development on housing cost and property values as the market evolves[13,16]
Determine the impact of oil and gas development on local infrastructure (e.g., healthcare services)[6,8]
REFERENCES
[1]Jackson et al. 2014; [2]Goldstein et al. 2014; [3]Moore et al. 2014b; [4]Brittingham et al. 2014; [5]Adgate et al. 2014; [6]Penning et al. 2014; [7]Jacquet 2014; [8]Maryland Institute for Applied Environmental Health 2014; [9]Souther et al. 2014; [10]Devlin et al. 2014; [11] National Research Council 2014b; [12]Witter et al. 2014; [13]Krupnick et al. 2014; [14]Shonkoff et al. 2014; [15] Multi-Agency, 2014; [16] Environmental Law Institute and Washington and Jefferson College Center for Energy Policy and Management 2014; [17]National Research Council 2013; [18]Vidic et al. 2013; [19]Drohan et al. 2012; [20]Brantley et al. 2014; [21]Davies et al. 2014; [22]National Research Council 2014a

The recommendations summarized in Table 6 illustrate the number and complexity of research paths that could be pursued, without a clear set of priorities among them. In recognition of this complexity, the Committee is developing a decision framework, along with criteria and weights assigned to each criterion, to guide its prioritization of research alternatives so that its research recommendations can be readily incorporated into a robust research program.

To facilitate good research planning, HEI and members of the Committee welcome (1) feedback on both this draft interim report and the initiative in general, (2) recommendations for research needs, and (3) recommendations for criteria to prioritize research alternatives. At its second public workshop, on December 10, 2014, in Wheeling, West Virginia, the Committee hopes to hear from interested parties who bring a broad perspective to questions about research needs. For example, the Committee would like to know the research priorities of people who work in the oil and gas industry, oversee some aspect of industry operations, conduct scientific research related to potential impacts, manage public lands on which oil and gas development occurs, are responsible for protecting public health of communities where oil and gas development is underway, live or work near oil and gas operations, represent the public in legislative bodies, and many others. Following this workshop, the Committee will begin considering research needs and ways to prioritize them, as discussed above, and comments received during and very soon after the workshop will be most useful in the process. A draft of the Committee's research plan will also undergo formal peer review and, after revisions, will be released in time for public review and discussion, including at the Committee's third public workshop, before being finalized in mid-2015 (Figure 15). HEI will share and discuss the final plan with public agencies, private industry, and community representatives, and other stakeholders at the state, regional, and national levels with the aim of engendering interest in and support for pursuing the filling of key knowledge gaps to inform better decisions on 21st century oil and gas development going forward.

Figure 15. Timeline and principal milestones for completion of the Committee's work.

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APPENDIX A: BIOGRAPHICAL SKETCHES

SCIENTIFIC COMMITTEE ON UNCONVENTIONAL OIL AND GAS DEVELOPMENT IN THE APPALACHIAN BASIN

BIOGRAPHICAL SKETCHES

HEI Special Scientific Committee on Unconventional Oil and Gas Development

George M. Hornberger (chair), *Vanderbilt University*
Alison C. Cullen, *University of Washington*
Jeffrey J. Daniels, *Ohio State University*
Alan M. Ducatman, *West Virginia University*
John K. Jackson, *Stroud Water Research Institute*
William (Bill) M. Kappel, *Hydrogeologist, retired*
Richard (Rick) S. Krannich, *Utah State University*
Vince Matthews, *Principal of Leadville Geology; former State Geologist of Colorado*
Allen L. Robinson, *HEI Research Committee and Carnegie Mellon University*
Dale P. Sandler, *National Institute of Environmental Health Sciences*
Susan L. Stout, *Federal Liaison, United States Department of Agriculture Forest Service*
Deborah L. Swackhamer, *University of Minnesota*
Junfeng (Jim) Zhang, *Duke University*

Special Advisors to the Committee:

Bernard Goldstein, *University of Pittsburgh*
Alan Krupnick, *Resources for the Future*
Michael E. Parker, *Parker Environmental and Consulting, LLC*

COMMITTEE MEMBERS

George M. Hornberger (Chair) is Distinguished University Professor at Vanderbilt University, where he is the Director of the Vanderbilt Institute for Energy and the Environment. He has a shared appointment as the Craig E. Philip Professor of Engineering and as Professor of Earth and Environmental Sciences. He previously was a professor at the University of Virginia for many years where he held the Ernest H. Ern Chair of Environmental Sciences. He also has been a visiting scholar at the Australian National University, Lancaster University, Stanford University, the United States Geological Survey (USGS), the University of Colorado, and the University of California at Berkeley. His research is aimed at understanding complex water-energy-climate interrelationships and at how hydrological processes affect the transport of dissolved and suspended constituents through catchments and aquifers. Dr. Hornberger is a fellow of the American Geophysical Union (AGU), a fellow of the Geological Society of America, and a fellow of the Association for Women in Science. He was President of the Hydrology Section of AGU from 2006-2008. He was a member of the Nuclear Waste Technical Review Board (a Presidential appointment) from April 2004 through August 2012. In 1996 he was elected to the

National Academy of Engineering. He has served on numerous boards and committees of the National Academies, including as chair of the Commission on Geosciences, Environment, and Resources (1996-2000) and chair of the Board on Earth Sciences and Resources (2003-2009). He currently is chair of the Water Science and Technology Board. He serves on the Advisory Committee for the Geosciences Directorate for the National Science Foundation and he chairs the Geoscience Policy Committee for the American Geosciences Institute. In 1993, Professor Hornberger won the Robert E. Horton Award (Hydrology Section) from the AGU; in 1995, he received the John Wesley Powell Award from the USGS; in 1999, he was presented with the Excellence in Geophysical Education Award by the AGU; in 2007 he was selected Virginia Outstanding Scientist; and he was the 2010 recipient of the William Kaula Award from AGU. Hornberger received his BS and MS from Drexel University and his PhD in hydrology from Stanford University.

Alison C. Cullen is a Professor at the Daniel J. Evans School of Public Affairs at the University of Washington. She specializes in the area of decision making under uncertainty related to environmental health decisions, in particular in the area of health risk analysis. Her foci include human exposure to toxic pollutants, energy and climate policy and management, the value of genetic and meta-genomic information to environmental regulation, and approaches to addressing uncertainty and variability in human health risk. Dr. Cullen works on a range of environmental and health decisions for which information is incomplete or unavailable for relevant geographic and temporal scales, and characterized by variable resilience across populations. She applies value of information analysis to weigh the potential relative advantages of making decisions with more refined information, when viewed in light of the consequences that accrue in its absence. Dr. Cullen currently serves on the United States Environmental Protection Agency (USEPA) Clean Air Scientific Advisory Committee and on the Alfred P. Sloan Foundation's Advisory Board on Synthetic Biology. She is a member of the Editorial Board for the journal Risk Analysis and is both a Fellow and a Past-President of the Society for Risk Analysis (SRA). Other professional honors include the International Society of Exposure Science Joan M. Daisey Award in 1998, the Chauncey Starr Award of SRA in 2002 and the USEPA's Special Recognition in the Field of Air Toxics in 2003. She holds a BS in Civil/Environmental Engineering from MIT and an MS and ScD in Environmental Health Science from the Harvard School of Public Health.

Jeffrey J. Daniels is a Professor of Geophysics at Ohio State University (OSU) and co-director of the OSU Subsurface Energy Resource Center (SERC). Dr. Daniels has been at OSU since 1985 where he is an applied geophysicist with a broad base of experience in surface and borehole geophysical methods applied to subsurface science. His research focuses on developing geophysical techniques to image objects and monitor gas and fluids in the subsurface. He is the author of over 100 publications in journals and proceedings, a book, and several book chapters. He regularly serves on professional panels (e.g., Committee on Institutional Cooperation Leadership Forum, National Research Council Committee on Subsurface Characterization), is currently a member of the Science Advisory Board for the U.S. Department of Defense's Strategic Environmental Research and Development Program (SERDP), and a member of the College of Reviewers for the Canada Research Chairs Program. He is the former co-chair of the

Energy Working Group for OSU (2006), a founding member and organizer of the University Clean Energy Alliance of Ohio (a consortium of Ohio's 15 research universities organized in 2007), and a prime mover in organizing the University Consortium for Futuregen (a consortium of 8 major universities in Ohio and the Midwest). He was also the prime mover, and technical Principal Investigator, of a successful proposal to the Third Frontier Program (Ohio Department of Development) for an Endowed Chair in Geologic Carbon Sequestration. He received his PhD in Geophysics from the Colorado School of Mines.

Alan M. Ducatman is a Professor in the School of Public Health and School of Medicine at West Virginia University. Dr. Ducatman's research interests include occupational and environmental toxicity and prevention of diseases potentially related to environmental exposures. His current environmental research focuses on the human population aspects of perfluorocarbon exposure. In addition to his teaching and research, he maintains an active referral clinic for patients concerned about chemical exposure concerns. Dr. Ducatman also collaborates with clinical laboratory scientists and clinicians to create comparative effectiveness research for laboratory utilization practices. For both types of research, his aspiration is to improve the health of populations. Dr. Ducatman received the MD degree from Wayne State University and the MSc in Environmental Health from the City University of New York. He completed his residency training at Brown University and at the Mayo Clinic, and he is board-certified in Internal Medicine and in Occupational Medicine. Dr. Ducatman is a frequent consultant to industry, government, nonprofit organizations, and patient or community groups regarding occupational and environmental health, and public health interventions. He has been a Department chair and interim founding dean of a new school of public health at West Virginia University. His national service includes chairmanship of the Residency Review Committee in Preventive Medicine, and Chairmanship of the Scientific Board of Counselors of the Agency for Toxic Substances and Disease Registry (ATSDR) – National Center for Environmental Health (NCEH) of the Centers for Disease Control.

John K. Jackson is a Principal Investigator of the Entomology group at the Stroud Water Research Center in Pennsylvania. He is also Adjunct Professor of Entomology and Applied Ecology at the University of Delaware and Adjunct Professor of Biology at the University of Pennsylvania. Dr. Jackson's research interests span a variety of applied and basic subjects, including population and evolutionary ecology of stream insects, the role of abiotic and biotic processes in determining the structure and function of stream assemblages, energy and nutrient exchange within streams and between streams and their surrounding watersheds, and benthic monitoring and water quality assessment. Specific projects that address these research interests include studies of growth and development of aquatic insects, the influence of dispersal, population dynamics, and environmental variation on genetic structure of stream organisms, the evolutionary and ecological significance of disturbance in aquatic insect ecology, spatial and temporal variation in the distribution and abundance of stream insects, and organic matter dynamics and secondary production. Dr. Jackson received his BS in Biology from the University of Notre Dame, his MS in Zoology from Arizona State University, and his PhD in Entomology from the University of California. In 1998, he was a Fulbright Senior Scholar at Institut fur Zoologie und Limnologie, Universitat Innsbruck, Austria.

William (Bill) M. Kappel is a hydrogeologist who served as the Section Chief of the Study Section for the U.S. Geological Survey Water Sciences Center in Ithaca, New York from 1979 to 2013. Since that time, Mr. Kappel continues to work with Emeritus status. He has extensive experience with water resource investigations. He coordinated USGS water resource information and study efforts related to shale gas development in New York and in collaboration with other Water Science Centers across the Marcellus 'Play' from West Virginia to New York. Mr. Kappel received his BS in Physical Sciences from Pennsylvania State University, and his MS in Forest Hydrology from Pennsylvania State University.

Richard (Rick) S. Krannich is Professor of Sociology, Director of the Institute for Social Science Research on Natural Resources and, beginning in July 2013, Director of the graduate program in Sociology at Utah State University. He joined the USU faculty in 1980 after receiving a PhD in Sociology from Pennsylvania State University. Dr. Krannich's research interests and experience include social impacts of oil and gas development and other extractive industries; public attitudes and actions pertaining to natural resource use and policy; social aspects of radioactive and hazardous waste management; human dimensions of wildlife management; and the socio-economic implications of large-scale renewable energy technologies. He has completed much research related to community adaptation and long-term social well-being in communities affected by energy-related boom growth. Currently he is engaged in research focusing on the implications of utility-scale renewable energy developments for social organization and social well-being in western rural communities. His recent professional activities have included service as editor of the journal Society and Natural Resources, as President of the Rural Sociological Society, and as Executive Director of the International Association for Society and Natural Resources. Dr. Krannich has also contributed to social assessment projects as a consultant for the Bureau of Land Reclamation, the USDA Forest Service, the Federal Energy Regulatory Committee, and other federal and state agencies.

Vince Matthews is a geologist who serves as Principal of Leadville Geology LLC, and recently was Interim Executive Director of the National Mining Hall of Fame and Museum. He retired as State Geologist and Director of the Colorado Geological Survey at the beginning of 2013. As a former executive in the natural resources industry for Amoco, Lear, Union Pacific, and Penn Virginia, Matthews explored for oil and gas in virtually every basin in the U.S., including Alaska and the Gulf of Mexico. Part of his experience in the natural resources industry included responsibility for coal, lime, and limestone activities in New Jersey, Virginia, and Tennessee. Vince received Bachelors and Masters degrees in Geology from the University of Georgia and a Ph. D. from the University of California, Santa Cruz and holds Outstanding Alumnus Awards from both institutions. He held tenured positions at two universities and has taught geology at the University of California, University of Northern Colorado, Arizona State University, the Frank Lloyd Wright School of Architecture, and the University of Texas of the Permian Basin. He is the author of more than 70 technical articles and abstracts and was senior editor of the multiple, award-winning publication, Messages in Stone: Colorado's Colorful Geology and the map, A Tourist Guide to Colorado Geology. Matthews is a Senior Fellow in the Geological Society of America where he served as General Chair of the 125th Anniversary Meeting last fall.

He is the 2014 recipient of the Pioneer Award from the American Association of Petroleum Geologists. Vince serves on the Board of Directors of the National Mining Hall of Fame and Museum, the Geology Advisory Committee at Colorado State University, and the Advisory Committee for the J. P. Morgan Center for Commodities of the University of Colorado-Denver's Business School.

Allen L. Robinson is the Raymond J. Lane Distinguished Professor and Head of the Department of Mechanical Engineering at Carnegie Mellon University. He is also a Professor in the Department of Engineering and Public Policy and a member of the Center for Atmospheric Particle Studies. Dr. Robinson first joined the faculty at Carnegie Mellon in 1998. Dr. Robinson's research examines the impact of emissions from energy systems on air quality and global climate. A major focus of his research has been the atmospheric transformation of particulate matter emissions from cars, trucks, and other combustion systems. He is also actively working on field measurements and chemical transport modeling to quantify the impact of emissions from unconventional gas development on local and regional air quality and climate. In 2012-2013, he was a faculty member at Colorado State University in the Departments of Atmospheric Science and Mechanical Engineering. In 2009-2010, he was a visiting faculty fellow at the Cooperative Institute for Research in Environmental Science at the University of Colorado in Boulder. He holds a BS in Civil Engineering from Stanford University, and an MS and PhD in Mechanical Engineering from the University of California at Berkeley. Dr. Robinson received the Carnegie Institute of Technology Outstanding Research Award in 2010, the Ahrens Career Development Chair in Mechanical Engineering in 2005, and the George Tallman Ladd Outstanding Young Faculty Award in 2000. He is currently serving on the Research Committee of the Health Effects Institute, the Environmental Protection Agency Clean Air Scientific Advisory Committee (CASAC) Air Monitoring and Methods Subcommittee, the Editorial Advisory Board of Aerosol Science and Technology, and the Editorial Board of Progress in Energy and Combustion Science. He has authored or co-authored more than 100 peer-reviewed archival journal papers. His research is supported by United States federal agencies (e.g., U.S. Environmental Protection Agency, Department of Energy, Department of Defense, Department of Interior, and the National Science Foundation), state and local government (e.g., the Allegheny County Health Department), industry (e.g., Electric Power Research Institute), and foundations (e.g., Heinz Endowments). Dr. Robinson teaches graduate and undergraduate courses on thermodynamics, atmospheric chemistry, air pollution control, climate change mitigation, combustion, and air quality engineering.

Dale P. Sandler is Chief of the Epidemiology Branch in the Division of Intramural Research at the National Institute of Environmental Health Sciences (NIEHS), National Institutes of Health, and head of the Chronic Disease Epidemiology Group. She is adjunct professor of Epidemiology at the University of North Carolina at Chapel Hill, past editor of the journals, Epidemiology and the American Journal of Epidemiology, and a past president of the American College of Epidemiology. Dr. Sandler has published more than 250 scientific articles, reviews and commentaries. She received an M.P.H. from Yale University in 1975 and a Ph.D. in Epidemiology from The Johns Hopkins University in 1979. Dr. Sandler's research focuses on risk factors for a wide range of chronic diseases, including chronic kidney disease, leukemia, and breast cancer. She has studied the role of early life and reproductive factors in risk for diseases later in life as well as potential health effects of passive smoking, radon and agricultural exposures. In 1993, Dr. Sandler partnered with investigators from the National Cancer Institute and the Environmental Protection Agency to develop the Agricultural Health Study, an ongoing prospective study of the health of licensed pesticide applicators and their spouses. She is Principal Investigator of The Sister Study, a prospective study of more than 50,000 sisters of women who have had breast cancer, which is designed to identify environmental and genetic factors that contribute to breast cancer risk and outcomes after diagnosis. A related study, The Two Sister Study, uses a family design to explore genetic and environmental risk factors for early onset breast cancer. More recently, Dr. Sandler became the Principal Investigator of a prospective study of the health of Gulf of Mexico Deepwater Horizon disaster clean-up workers. This study, known as the GuLF STUDY, has recruited nearly 33,000 persons involved in some aspect of oil-spill clean-up and carried out home-based clinical assessments with more than 11,000 persons living in Gulf states.

Susan L. Stout (Federal Liaison to the committee) is a Research Project Leader and Research Forester at the Northern Research Station of the United States Department of Agriculture Forest Service in Irvine, PA. She has served in this position since 1991; before that, she was a Research Forester with the Northeastern Research Station from 1981-1991. She received her A.B. from Radcliffe College of Harvard University, her M.S. in Silviculture from the State University of New York, and her D.F. from Yale University. Her research interests include measuring crowding and diversity in forests, deer impact on forests, silvicultural systems, and translating results from ecosystem research into practical management guidelines for Pennsylvania's forests and beyond. Since 2011, Stout has been a regional co-lead on identifying research needs related to oil and gas development for the Northern Research Station. This team co-sponsored the 2012 Penn State Goddard Forum, "Oil and Gas Impacts on Forest Ecosystems: Research and Management Challenges." In addition, Dr. Stout was the US Forest Service representative to a federal interagency task force concerning research needs related to unconventional oil and gas development. Dr. Stout was named a Fellow of the Society of American Foresters in 2003.

Deborah L. Swackhamer is a Professor of Science, Technology, and Public Policy in the Humphrey School of Public Affairs, and a Professor of Environmental Health Sciences in the School of Public Health at the University of Minnesota. She also directed the Water Resources Center from 2002 until 2014. She received a BA in Chemistry from Grinnell College, IA and MS and PhD degrees from the University of Wisconsin-Madison in Water Chemistry and Limnology & Oceanography, respectively. After two years of post-doctoral research in Chemistry and Public & Environmental Affairs at Indiana University, she joined the Minnesota faculty in 1987. She studies the processes affecting the behavior of and exposures to toxic chemicals in the environment, and she works on policies to address these potential risks. In 2012 Dr. Swackhamer completed a 4-year term as Chair of the Science Advisory Board of the U.S. Environmental Protection Agency (USEPA), and served as a member of the Science Advisory Board of the International Joint Commission of the U.S. and Canada from 2000-2013. She recently served on the National Research Council, National Academy of Sciences (NAS) committee addressing Sustainability Linkages in the Federal Government and currently serves on the NAS Committee evaluating the USEPA Laboratory Enterprise. She is a Governor appointee on the Minnesota Clean Water Council and was President of the National Institutes of Water Resources in 2011-2012. Dr. Swackhamer is a member of the Editorial Advisory Board for the journal Environmental Science & Technology, is a Fellow in the Royal Society of Chemistry in the UK, and is the recipient of the 2007 Harvey G. Rogers Award from the Minnesota Public Health Association. In 2009 she received the prestigious Founders Award from the Society of Environmental Toxicology and Chemistry for lifetime achievement in environmental sciences. She was also the 2010 recipient of the University of Minnesota's Ada Comstock Award.

Junfeng (Jim) Zhang is a Professor of Global and Environmental Health and Director of the Exposure Biology and Chemistry Laboratory at Duke University's Nicholas School of the Environment & Duke Global Health Institute. Dr. Zhang joined the Duke Faculty in the Fall of 2013 from the University of Southern California where he had been a Professor of Environmental and Global Health and Director of the Environmental and Biomarkers Analysis Laboratory since 2010. His prior positions include Professor, Department Chair, and Associate Dean at the Rutgers School of Public Health. Dr. Zhang has more than 140 peer-reviewed publications. His work has been featured in major international media such as Time, the New York Times, BBC, ABC, CBS, and Yahoo News. His early work on characterizing sources of non-methane greenhouse gases made him one of the officially recognized contributors to the 2007 Nobel Peace Prize awarded to the Intergovernmental Panel on Climate Change. He is the 2012 recipient of the Jeremy Wesolowski Award, the highest award of the International Society of Exposure Science. He also received a Distinguished Alumni Award from the Rutgers Graduate School. Dr. Zhang's research interests include developing novel biomarkers of human exposure and health effects, assessing health and climate co-benefits of air pollution interventions, and examining biological mechanisms by which environmental exposures exert adverse health effects. Dr. Zhang has led a number of international collaborations to study air pollution health effects and underlying pathophysiologic mechanisms. He is currently leading two multidisciplinary, multi-institutional centers studying the health impact of engineered nanomaterials.

SPECIAL ADVISORS

Alan Krupnick is the Founder and Director of the Center for Energy Economics and Policy (CEEP) and a Senior Research Fellow at Resources for the Future (RFF). Dr. Krupnick is also the President and a Fellow of the Association of Environmental Resource Economists (AERE). He has served regularly on expert committees from the US EPA and the National Academy of Sciences, and has co-chaired a federal advisory committee to the US EPA regarding the implementation of new ozone and particulate standards. From 1993-1994 he served as a senior economist on the President's Council of Economic Advisors, advising the Clinton administration on environmental and natural resource policy issues. Dr. Krupnick has been a consultant to State Governments, federal agencies, private corporations, the European Union, the World Health Organization, the World Bank, and various Canadian Health and Environmental organizations. He has served on the editorial board of *Land Economics*, and has been a reviewer and/or contributor to a myriad of other journals and publications such as the *American Economic*

Review, the *Journal of Environmental Economics and Management,* and the *Oxford University Press*. His current research focuses on analyzing environmental and energy issues and focuses on topics such as air quality, ecosystems, energy, international policy and analysis, risk management, and transportation. As director of the CEEP, Dr. Krupnick is currently leading research on the risks and issues associated with shale gas development. His primary research methodology is to utilize stated preference surveys such as contingent valuation and choice experiments. Dr. Krupnick received his BA from Pennsylvania State University and his MA and PhD in economics from the University of Maryland.

Bernard D. Goldstein is Emeritus Professor of Environment and Occupational Health and former Dean of the University of Pittsburgh's Graduate School of Public Health. He is a physician, board certified in internal medicine, hematology, and toxicology. Dr. Goldstein is author of more than 150 publications in the peer-reviewed literature, as well as numerous reviews related to environmental health. He is an elected member of the IOM and of the American Society for Clinical Investigation. His experience includes service as assistant administrator for research and development of the EPA, 1983–1985. In 2001, he joined the University of Pittsburgh from New Jersey, where he had been the founding director of the Environmental and Occupational Health Sciences Institute, a joint program of Rutgers University and Robert Wood Johnson Medical School. He has chaired more than a dozen National Research Council (NRC) and IOM committees primarily related to environmental health issues. He has been president of the Society for Risk Analysis; and has chaired the NIH Toxicology Study Section, EPA's Clean Air Scientific Advisory Committee, the National Board of Public Health Examiners, and the Research Committee of the Health Effects Institute. He has also served as a member or chairperson of numerous national and international scientific advisory committees for government, industry, and environmental groups.

Michael E. Parker is currently Principal of Parker Environmental and Consulting, LLC, which provides environmental and regulatory policy development, technical, and advocacy support on a range of issues, focusing on nonconventional oil and gas development including hydraulic fracturing, produced water management, water resource management, onshore and offshore environmental management issues, and carbon capture and storage issues. Prior to establishing his consulting practice, Mr. Parker worked for ExxonMobil Production Company for over 35 years in a variety of engineering and technical assignments. At retirement, Mr. Parker was a Technical Advisor in ExxonMobil's Upstream Safety, Health, and Environment organization. Mr. Parker provided technical support and guidance to ExxonMobil affiliates world-wide on a range of issues including drilling and production discharges, underground injection control, spill prevention and control, facility decommissioning, artificial reef programs, marine environmental issues, carbon capture and storage, hydraulic fracturing and general issue management coordination. Mr. Parker has served as Chair of the American Petroleum Institute's Upstream Environmental Subcommittee, the Hydraulic Fracturing Workgroup, the Carbon Capture and Storage Work Group and the Water Issues Group and is currently involved in the revisions to API's HF Guidance Documents and Recommended Practices. Mr. Parker is a graduate of the University of Texas and Texas A&M University and is a registered Professional Engineer in Texas and Louisiana.

APPENDIX B: GLOSSARY

SCIENTIFIC COMMITTEE ON UNCONVENTIONAL OIL AND GAS DEVELOPMENT IN THE APPALACHIAN BASIN

GLOSSARY

A

Abandon - To cease producing oil or gas from a well when it becomes unprofitable. A wildcat (see "Wildcat") may be abandoned after it has been proven nonproductive. Usually, when a well is abandoned, some of the casing is removed and salvaged and one or more cement plugs are placed in the borehole to prevent migration of fluids between the various formations. In many States, abandonment must be approved by an official regulatory agency before being undertaken.

Acidize - To treat oil-bearing limestone or other formations, using a chemical reaction with acid, to increase production.

Annulus - The space around a pipe in a wellbore, the outer wall of which may be the wall of either the borehole or the casing.

Appalachian Basin - The geological formations that roughly follow the Appalachian Mountain range and contain potentially exploitable shale gas resources. The U.S. Department of Energy (DOE) associates the Appalachian Basin with the Marcellus Shale, the Devonian Shale and the Utica Shale.

B

Basin - A synclinal structure in the subsurface, formerly the bed of an ancient sea. Because it is composed of sedimentary rock and its contours provide traps for petroleum, a basin is a good prospect for exploration. For example, the Permian Basin in West Texas is a major oil producer.

Biogenic methane, or biogenic gas (also known as microbial methane or gas) - methane produced by microbes as they decompose organic matter, usually from surficial sources (landfills, septic systems, or naturally-buried organic material)

Blow Out - To suddenly expel oil/gas-well fluids from the borehole with great velocity.

Brine[**] **-** Water containing more dissolved inorganic salt than typical seawater.

C

Casing - Heavy steel pipe place in an open hole and cemented into place. Casing is designed to withstand high pressures, large tensile loads and resist chemical reaction and corrosion. A casing string refers to a series of connected segments of casing or pipe that serves to prevent the hole from caving, keep the fluids inside the casing string from migrating to porous formations, prevent unwanted fluids from entering the hole, and protect fresh water aquifers.

[**] Signifies that the definition was found in the OSHA (Occupational Health and Safety Administration) Oil and Gas Well Drilling and Servicing online glossary (https://www.osha.gov/doc/outreachtraining/htmlfiles/hazglos.html)

Cementing - Placing a cement mixture between the casing and a borehole to stabilize the casing and seal off the formation.

Cement Plug - A portion of cement placed at some point in the wellbore to seal it.

Coalbed methane (CBM) - Coalbed methane is a form of natural gas generated by and extracted from coal beds. In recent decades it has become an important source of energy in the United States and other countries.

Completion Operations - Work performed in an oil or gas well after the well has been drilled to the point at which the production string of casing is to be set. This work includes setting the casing, perforating, artificial stimulation, production testing, and equipping the well for production, all prior to the commencement of the actual production of oil or gas in paying quantities, or in the case of an injection or service well, prior to when the well is plugged and abandoned.

Compressor Station – Any combination of facilities that supply the energy to move gas in transmission or distribution lines or into storage by increasing the pressure. Compressor stations might include equipment to remove liquids, particles, and other impurities from the natural gas, which are disposed of or sold as desired.

Condensate - A light hydrocarbon liquid obtained by condensation of hydrocarbon vapors. It consists of varying proportions of butane, propane, pentane, and heavier fractions, with little or no ethane or methane.

Conductor Casing - A short string of large-diameter casing used offshore and in marshy locations to keep the top of the wellbore open and to provide a means of conveying the up-flowing drilling fluid from the wellbore to the mud pit.

Continuous (Unconventional) Hydrocarbon Resource - Continuous resources (including accumulations known as basin-centered gas, shale gas, tight gas, and coalbed gas) were defined as those accumulations generally not trapped by hydrodynamic processes. Transition zones were recognized between areas of conventional and continuous resources. A continuous oil or gas accumulation may have some or all of the following characteristics - (1) regional in extent, (2) diffuse boundaries, (3) existing “fields” commonly merge into a single regional accumulation, (4) no obvious seal and trap, (5) no well-defined, oil- or gas-water contact, (6) hydrocarbons apparently not held in place by hydrodynamics, (7) commonly abnormally pressured, (8) large in-place resource volume, but very low recovery factor, (9) geologically controlled “sweet spots”, (10) little free water production (except from coal-bed gas accumulations), (11) water commonly found up dip from hydrocarbons, (12) few truly “dry” holes, (13) reservoirs generally in close proximity to source rocks, (14) Estimated Ultimate Recovery (EUR) of oil or gas from wells are generally lower than EURs from wells in a conventional accumulation, 15) reservoirs with very low matrix permeabilities, and (16) natural reservoir fracturing common.

Conventional oil and gas accumulations - Are discrete accumulations with well-defined hydrocarbon-water contacts, where the hydrocarbons are buoyant on a column of water. Conventional accumulations commonly have relatively high matrix permeabilities, have obvious seals and traps, and have relatively high recovery factors.

Conventional oil and natural gas production - Crude oil and/or natural gas that is produced by a well drilled into a geologic formation in which the reservoir and fluid characteristics permit the oil and/or natural gas to *readily flow* to the wellbore.

Cuttings – see "Drill Cuttings"

D

Dehydrator - removes water from natural gas

Drill Cuttings -** Fragments of rock dislodged by the drill bit and brought to the surface in the drilling mud. Washed and dried cuttings samples are analyzed by geologists to obtain information about the formations drilled.

Drilling mud or drilling fluid: a mixture of a liquid base (water, oil or synthetic chemicals), clays and chemicals, used to lubricate and cool the drill bit as it creates the wellbore. The mud also transports the drill cuttings to the surface and helps control pressure within the well. Compressed air may be used instead of mud.

Drill Rig - a machine that contains the equipment to drill the wellbore—the hole in the ground that goes into the shale formation.

Dry Natural Gas – Natural gas which remains after: 1) the liquefiable hydrocarbon portion has been removed from the gas stream; 2) any volumes of non-hydrocarbon gases have been removed where they occur in sufficient quantity to render the gas unmarketable.

F

Field - An accumulation, pool, or group of pools of hydrocarbons or other mineral resources in the subsurface. A hydrocarbon field consists of a reservoir with trapped hydrocarbons covered by an impermeable sealing rock, or trapped by hydrostatic pressure.

Flowback water - Water that returns to the surface after the hydraulic fracturing process is completed and the pressure is released and before the well is placed in production; flowback water return occurs for several weeks.

Formation - A body of rock strata, of intermediate rank in the hierarchy of lithostratigraphic units, which is unified with respect to adjacent strata by consisting dominantly of a certain lithologic type, or by possessing other unifying lithologic features.

Formation Fluid - The water originally in place in a formation.

Flare – Burners used to combust excess gases. Flaring is a form of air pollution control, but less effective than capturing the gas in pipelines. It can be used as a safety device, to prevent the buildup of dangerous gases. Flaring also produces pollutants such as soot and dioxins. Sustained flaring of the associated natural gas from oil wells aggravates climate change and wastes the methane that could be used as an energy source.

Flowback: the mixture of drilling mud, fracturing fluids, produced water, oil, gas, salts, heavy metals, and natural gas liquids that comes out of a well after hydraulic fracturing. Flowback contains toxic compounds that must be treated or disposed of.

Frac pumps: used to pump fracturing fluids into the well

Fracturing fluid: Composed of mostly water, with small percentages of proppants and chemicals. The chemicals used are a mixture of benign products (guar gum) and toxic compounds (carcinogens like benzene). Some of the chemicals are harmful at concentrations of parts per million or parts per billion when released into the water or air. Many types of fracturing fluids are used, with proprietary compositions, and the technology is constantly evolving. Although the chemicals make up a tiny fraction of the fracturing fluids (sometimes less than 1 percent), the overall volumes are so high that a single well often requires tens of thousands of gallons of chemicals.

Fugitive Emission – Intentional or unintentional release of greenhouse gases that may occur during extraction, processing and delivery of fossil fuels to the point of final use. While methane (CH4) is the predominant type of greenhouse gas emitted as a fugitive emission in the oil and gas sector, noteworthy fugitive emissions of carbon dioxide (CO2) and, to a much lesser extent, nitrous oxide (N2O), may also occur

G

Gas - Also referred to as natural gas, is a naturally occurring hydrocarbon gas mixture consisting primarily of methane with up to 20 percent of other hydrocarbons as well as impurities in varying amounts.

Gas Reservoir - A subsurface accumulation of hydrocarbons primarily in the gas phase that is contained in porous or fractured rock formations.

Gas Well – A well completed for the production of natural gas from one or more gas zones or reservoirs. Such wells contain no completion for the production of crude oil.

Gathering Pipeline - A pipeline, usually of small diameter, used in gathering crude oil or natural gas from a well or well field to a point on a main pipeline.

Generators: Usually powered by diesel. Needed to provide electricity for lights, hydraulic pumps, etc. because most well pads are in remote locations off the grid. Once a well is in the production phase, electricity is often routed to the well pad, and the generators are removed.

H

Horizontal or directional drilling: an advanced drilling method where the wellbore is first drilled vertically, then gradually turned until it's sandwiched within the shale layer. A horizontal well can go on for more than a mile within the shale.

Hydraulic fracturing: an oil and gas stimulation method first introduced commercially in the 1940s, when water and sand were pumped underground to free up tightly-bound oil and gas. The process has a evolved a lot since then. For increased efficiency, companies experimented by pumping down brine, diesel, and mixtures of chemicals. The type of fracturing used today—high volume hydraulic fracturing—is quite different from the 1940's technique: there's a lot more pressure, greater use of chemicals and much higher amounts of fracturing fluids, up to millions of gallons per well. That's because many wells are created via horizontal drilling, and the deeper, longer wells require more liquids to fracture. The combination of high-volume fracturing and horizontal drilling is responsible for the recent shale boom.

High Volume Hydraulic Fracturing (HVHF) – A term that denotes the newer form of hydrocarbon development from tight shale and sandstone formations. Related to unconventional- continuous hydrocarbon resource development, but in particular, that which has been evolving (and continues to evolve) over the last ~ 20 years.

Hydrocarbons - Organic compounds of hydrogen and carbon, whose densities, boiling points, and freezing points increase as their molecular weights increase. Although composed of only two elements, hydrocarbons exist in a variety of compounds because of the strong affinity of the carbon atom for other atoms and for itself. The smallest molecules of hydrocarbons are gaseous; the largest are solid.

M

Marcellus Formation – An organic carbon-rich black shale which underlies an area of approximately 95,000 mile^2 along the Appalachian basin.

Microbial methane, or microbial gas (also known as biogenic methane or gas) - methane produced by microbes as they decompose organic matter, usually from surficial sources (landfills, septic systems, or naturally-buried organic material)

Mud – See "Drilling mud"

N

Natural Gas - See also "gas." Hydrocarbons that exist as a gas or vapor at ordinary pressure and temperature. Methane is the most important, but ethane, propane, and others may be present. Common impurities include nitrogen, carbon dioxide, and hydrogen sulfide. Natural gas may occur alone or associated with oil.

Natural Gas Field - A region or area that possesses or is characterized by natural gas.

Natural gas liquids: a mix of hydrocarbons present in natural gas and oil wells. These compounds, which include ethane, propane, butane, pentane and hexane, are used as feedstock in chemical plants and refineries. The larger hydrocarbons in natural gas liquids (mostly pentanes and above) are collectively referred to as condensate.

Natural gas wells: wells that extract the raw natural gas that comes out of the ground, which contains methane (the target compound) and sometimes includes various impurities: water, carbon dioxide, VOCs, H2S, natural gas liquids and condensate. The relative amounts of these impurities varies by formation and well. "Sour" wells have higher levels of H2S. Gas wells are considered "dry" if they contain only methane, or only methane and water without the other impurities.

NORM (Naturally Occurring Radioactive Materials) - All naturally occurring radioactive materials where human activities have increased the potential for exposure compared with the unaltered situation.

O

Oil - A naturally occurring complex liquid hydrocarbon, which after distillation and removal of impurities yields a range of combustible fuels, petrochemicals, and lubricants. Crude oil refers to oil as it emerges from a well but before refining or distillation.

Oil/Gas Field - The surface area overlying an oil/gas reservoir or reservoirs. Commonly, the term includes not only the surface area but also the reservoir, wells, and production equipment.

Oil wells: wells that produce oil and natural gas liquids. Most oil wells in the Eagle Ford contain oil, gas and natural gas liquids. Operators will decide what to do with each type of product depending on market forces. Natural gas liquids are used in petrochemical plants and refineries. Due to the low price of natural gas, some operators will burn off (flare) the associated gas from oil wells because it's cheaper than building pipelines to collect the gas.

P

Perforate - To pierce the casing wall and cement to provide holes through which formation fluids may enter or to provide holes in the casing so that material may be introduced into the annulus between the casing and the wall of the borehole. Perforating is accomplished by lowering into the well a perforating gun, or perforator, that fires bullets org' shaped charges that are electrically detonated from the surface.

Permeability - A measure of the ease with which fluids can flow through a porous rock.

Porosity - The quality or state of possessing pores (as a rock formation). The ratio of the volume of interstices of a substance to the volume of its mass.

Produced water: Naturally-occurring water from the shale formation that flows out of the well after fracturing. Produced water contains salts, heavy metals, leached minerals, dissolved solids, naturally-occurring radiation and other toxic compounds.

Production - The phase of the petroleum industry that deals with bringing the well fluids to the surface and separating them and with storing, gauging, and otherwise preparing the product for the pipeline.

Production Casing - The last string of casing or liner that is set in a well, inside of which is usually suspended the tubing string.

Proppant (Propping agent)- a granular substance (silica sand, aluminum pellets, or other material) that is carried in suspension by the fracturing fluid and that serves to keep the cracks open when fracturing fluid is withdrawn after a fracture treatment.

R

Recoverability - The condition of being physically, technologically, and economically extractable. Recovery rates and recovery factors may be determined or estimated for coal resources without certain knowledge of their economic minability; therefore, the availability of recovery rates or factors does not predict recoverability.

Reserves - Are those quantities of petroleum anticipated to be commercially recoverable by application of development projects to known accumulations from a given date forward under defined conditions. Reserves must further satisfy four criteria - they must be discovered, recoverable, commercial, and remaining (as of the evaluation date) based on the development project(s) applied.

Reserve Pit - Drilling related pit used to store and/or dispose of used drilling muds and drill cuttings.

Reservoir - A subsurface, porous, permeable rock body in which oil or gas or both are stored. Most reservoir rocks are limestones, dolomites, sandstones, or a combination of these. The three basic types of hydrocarbon reservoirs are oil, gas, and condensate. An oil reservoir generally contains three fluids - gas, oil, and water- with oil the dominant product. In the typical oil reservoir, these fluids occur in different phases because of the variance in their gravities. Gas, the tightest, occupies the upper part of the reservoir rocks; water, the lower part; and oil, the intermediate section. In addition to occurring as a cap or in solution, gas may accumulate independently of the oil; if so, the reservoir is called a gas reservoir. Associated with the gas, in most instances, are salt water and some oil. In a condensate reservoir, the hydrocarbons may exist as a gas, but when brought to the surface, some of the heavier ones condense to a liquid or condensate. At the surface the hydrocarbons from a condensate reservoir consist of gas and a high-gravity crude (i.e., the condensate). Condensate wells are sometimes called gas-condensate reservoirs.

S

Sandstone - A sedimentary rock composed of individual mineral grains of rock fragments between 0.06 and 2 millimeters (0.002 and 0.079 inches) in diameter and cemented together by silica, calcite, iron oxide, and so forth. The relatively high porosity and permeability of sandstones make them good reservoir rocks.

Sediment - The matter that settles to the bottom of a liquid; also called tank bottoms, basic sediment, and so forth

Separator - An item of production equipment used to separate the liquid components of the well stream from the gaseous elements. Separators are vertical or horizontal and are cylindrical or spherical in shape. Separation is accomplished principally by gravity, the heavier liquids falling to the bottom and the gas rising to the top. A float valve or other liquid-level control regulates the level of oil in the bottom of the separator.

Shale: a type of sedimentary rock. Because oil and gas are tightly bound within the shale, operators almost always need hydraulic fracturing or another stimulation method to increase the shale's permeability so oil and gas can flow out of the well.

Shale Gas - Shale gas refers to natural gas that can be generated and trapped within shale units.

Shale Shaker - A series of trays with sieves that vibrate to remove cuttings from the circulating fluid in rotary drilling operations. The size of the openings in the sieve is carefully selected to match the size of the solids in the drilling fluid and the anticipated size of cuttings. It is also called a shaker.

Sour Gas - Natural gas or any other gas that contains hydrogen sulfide or another sulfur compound. Natural gas is usually considered "sour" if there is more than 5.7 milligrams H_2S per cubic meter of natural gas

Source Rock - Rocks containing relatively large amounts of organic matter that is transformed into hydrocarbons.

Stray Gas - Gas contained in the geologic formation outside the wellbore that may be mobilized by drilling and/or hydraulic fracturing or may migrate naturally along fractures or enter an uncased (in bedrock) drinking-water well. (Government Accountability Office, 2014, EPA Program to Protect Underground Sources from Injection of Fluids Associated with Oil and Gas Production Needs Improvement: Washington, DC, Government Accountability Office report GAO-14-555, 103p.)

Sweet Gas – Natural gas that does not contain significant amounts of hydrogen sulfide.

T

Thermogenic methane, or thermogenic gas - methane produced by intense heat and pressure within organic-rich bedrock such as the Marcellus shale

Tight Gas - Is natural gas trapped in a highly mixed mineralogy sandstone, shale, or limestone formations which has very low permeability and porosity. While conventional natural gas accumulations, once drilled, contain gas that can usually be extracted quite readily and easily, a great deal more effort, including hydraulic fracturing, has to be put into extracting gas from a tight formation.

Tight rock - Describing a relatively impermeable reservoir rock from which hydrocarbon production is difficult. Reservoirs can be tight because of smaller grains or matrix between larger grains, or they might be tight because they consist predominantly of silt- or clay-sized grains, as is the case for shale reservoirs

Trap - A geologic feature that permits the accumulation and prevents the escape of accumulated fluids (hydrocarbons) or injected carbon dioxide from the reservoir.

Tubing - Small diameter pipe that is run into a well to serve as a conduit for the passage of oil and gas to the surface.

U

Unconventional Hydrocarbon Resource - see "Continuous (Unconventional) Hydrocarbon Resource"

Unconventional Oil and Natural Gas Production* - An umbrella term for oil and natural gas that is produced by means that do not meet the criteria for conventional production. See Conventional oil and natural gas production. Note - What has qualified as "unconventional" at any particular time is a complex interactive function of resource characteristics, the available exploration and production technologies, the current economic environment, and the scale, frequency, and duration of production from the resource. Perceptions of these factors inevitably change over time and they often differ among users of the term

V

Vented Gas – Gas released into the air on the production site or at processing plants.

Volatile - Readily vaporized.

W

Wellbore - A borehole; the hole drilled by the bit. A wellbore may have casing in it or may be open (i.e., uncased); or a portion of it may be cased and a portion of it may be open.

Well Completion - The activities and methods necessary to prepare a well for the production of oil and gas; the method by which a flow line for hydrocarbons is established between the reservoir and the surface. The method of well completion used by the operator depends on the individual characteristics of the producing formation or formations. These techniques include open-hole completions, conventional perforated completions, sand-exclusion completions, tubingless completions, multiple completions, and miniaturized completions.

Wellhead - The equipment used to maintain surface control of a well, including the casing head, tubing head, and Christmas tree.

Well pad: a central location for the wells and equipment. A well pad may be several acres in size. Operators often place multiple wells on a single well pad

Well Stimulation - Any of several operations used to increase the production of a well.

Wet Gas - Natural gas that contains less methane (typically less than 85% methane) and more ethane and other more complex hydrocarbons.

Wildcat - A well drilled in area where no oil or gas production exists.

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