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Strategic Research Agenda on the Potential Impacts of 21st Century Oil and Natural Gas Development in the Appalachian Region and Beyond

HEI Special Scientific Committee on Unconventional Oil and Gas Development in the Appalachian Basin

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Health Effects Institute
Boston, MA

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ABOUT HEI

The Health Effects Institute is a nonprofit corporation chartered in 1980 as an independent research organization to provide high-quality, impartial, and relevant science on the effects of air pollution on health. To accomplish its mission, the institute

- Identifies the highest-priority areas for health effects research;
- Competitively funds and oversees research projects;
- Provides intensive independent review of HEI-supported studies and related research;
- Integrates HEI's research results with those of other institutions into broader evaluations; and
- Communicates the results of HEI's research and analyses to public and private decision makers.

HEI typically receives balanced funding from the U.S. Environmental Protection Agency and the worldwide motor vehicle industry. Frequently, other public and private organizations in the United States and around the world also support major projects or research programs. This Research Agenda was produced with funding from the Richard King Mellon Foundation, the Henry L. Hillman Foundation, the Claude Worthington Benedum Foundation, and the Henry C. and Belle Doyle McEldowney Fund of The Pittsburgh Foundation.

Since its inception HEI has funded more than 330 research projects in North America, Europe, Asia, and Latin America, the results of which have informed decisions regarding carbon monoxide, air toxics, nitrogen oxides, diesel exhaust, ozone, particulate matter, and other pollutants. These results have appeared in more than 260 comprehensive reports published by HEI, as well as in more than 1000 articles in the peer-reviewed literature.

HEI's independent Board of Directors consists of leaders in science and policy who are committed to fostering the public–private partnership that is central to the organization. The Health Research Committee solicits input from HEI sponsors and other stakeholders and works with scientific staff to develop a Five-Year Strategic Plan, select research projects for funding, and oversee their conduct. The Health Review Committee, which has no role in selecting or overseeing studies, works with staff to evaluate and interpret the results of funded studies and related research. For this Research Agenda, the HEI Board of Directors appointed a Special Scientific Committee on Unconventional Oil and Gas Development in the Appalachian Basin.

All HEI project results are widely disseminated through HEI's Web site (*www.healtheffects.org*), newsletters and other publications, annual conferences, and presentations to legislative bodies and public agencies.

CONTRIBUTORS

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

In 2014, HEI convened a special scientific committee to explore, define, and assess the potential human health, ecological, environmental, and social impacts of 21st century oil and natural gas development in the Appalachian Basin and to use its assessment to develop a Strategic Research Agenda to help guide the study of these potential impacts. The committee was 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 natural gas development and its potential impacts. Special advisors and consultants contribute additional areas of expertise.

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EXECUTIVE SUMMARY

Unconventional oil and natural gas development is a driving force behind significant economic and energy policy shifts in the United States and the world today. Technological advances in development are substantially increasing energy supplies, while at the same time outpacing the scientific research that can answer questions about the development's potential effects. With funding from private foundations, the Health Effects Institute (HEI) convened a Special Scientific Committee to develop this impartial, multidisciplinary Strategic Research Agenda to help guide future research about potential adverse impacts[1] of 21st century oil and natural gas development. The Research Agenda recommends research to better understand and to prevent or minimize potential impacts on human health and well-being, communities, ecological health, and the environment. The result of the Committee's work is this Strategic Research Agenda. It was developed in response to questions raised in the Appalachian region of the United States. The questions are not unique to the region; therefore, the Research Agenda can address concerns expressed elsewhere in the United States and the world.

As used in this Research Agenda, "21st century oil and natural gas development" refers to the onshore development and production of oil and natural gas from

Purpose and Scope of this Research Agenda

This Strategic Research Agenda is offered as an impartial, multidisciplinary guide for future research about potential adverse impacts of 21st century oil and natural gas development. The Research Agenda recommends research to better understand and to prevent or minimize potential impacts on human health and well-being, communities, ecological health, and the environment.

As used in the Research Agenda, "21st century oil and natural gas development" refers to the onshore development and production of oil and natural gas from unconventional geologic resources as practiced today, recognizing that industry practices continue to change in response to evolving technologies, regulations, and other factors. For simplicity, the term is abbreviated as "OGD" in this report.

Although the Committee recognized that OGD can generate important benefits, an in-depth analysis of such benefits was beyond the scope of our review. An equally important question also considered beyond the scope of the review is *How do potential OGD impacts compare with those from other energy sources?* Governmental agencies and other organizations are actively engaged in the complex task of evaluating various combinations of energy sources, including a consideration of their ability to meet future energy requirements and climate-change potential. The Committee has sought to answer the more focused but critical question to help inform future energy policy choices: *Which potential impacts of OGD warrant priority consideration for scientific study?*

Overview of Recommendations

The Committee defined research questions that:

- → Collectively indicate knowledge gaps; they are not findings of impacts;
- → Are linked to the ultimate goal of understanding and preventing or minimizing potential impacts on human and ecological health and well-being; and
- → Apply broadly to Appalachia and other regions.

Moving Forward

In view of the importance of implementing the Research Agenda as quickly as possible, HEI has already begun outreach to key potential partners and sources of funding from government, industry and the foundation community. The Research Agenda will form the basis of a targeted HEI Research Program, which will be described in a draft Implementation Plan to be released in late 2015.

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[1] Throughout this Research Agenda, the term "impact" refers to adverse effects. The term "benefit" refers to positive effects.

unconventional geologic resources as practiced today, recognizing that industry practices continue to change in response to evolving technologies, regulations, and other factors. The Committee chose the term (instead of the more common “unconventional oil and natural gas development”) to reflect the Committee’s intent (1) to address the potential impacts of oil and natural gas development that involves staged hydraulic fracturing (i.e., fracturing that occurs in sequential stages along a horizontal wellbore) combined with horizontal drilling used in the Appalachian region since the natural gas boom began and (2) to reflect the possibility that these technologies will be used more widely with both conventional and unconventional geologic formations in the future. For simplicity, the term is abbreviated as “OGD” in this report.

MOTIVATION FOR CREATING A RESEARCH AGENDA

Oil and natural gas development is not new to Appalachia, with hundreds of thousands of oil and natural gas wells drilled into primarily conventional geologic formations since the mid-1800s. Historically, oil and natural gas were extracted either without hydraulic fracturing or with lower volumes of hydraulic fracturing fluid. The extraction technique of staged hydraulic fracturing combined with horizontal drilling drives the current wave of development. OGD differs from previous oil and natural gas development in ways that introduce the potential for different kinds of impacts.

The use of the OGD processes in Pennsylvania began in the early 2000s and rapidly expanded to include eastern Ohio and northern West Virginia. Many people living in these regions were familiar with conventional oil and natural gas development, but not with the pace, scale, or type of the recent OGD. The industry and regulators have protocols to protect workers, neighbors, and the environment. However, given the rapid pace and technologic changes associated with OGD, knowledge of its potential impacts and whether protocols and regulations are sufficient to prevent or minimize them has, in some cases, lagged behind.

In response to shale gas development in Appalachia, various organizations — each with its own specific focus — have acted to understand, prevent, and minimize potential impacts. One of these organizations was the Pennsylvania-based Shale Gas Roundtable, composed of leaders from government, industry, academia, environmental groups, and the public (*http://iop.pitt.edu/shalegas/*). The Roundtable was formed to answer one question:

> As a region, how can we most effectively and responsibly
> safeguard our communities and environment, grow our economy,
> and manage unconventional oil and gas development?

In its 2013 report, the Roundtable emphasized the need for “efforts to increase balanced research and rigorous monitoring of the possible impacts of unconventional oil and gas development.” HEI’s multidisciplinary Special Scientific Committee, which produced the Research Agenda presented here, was formed in response to this recommendation.

THE COMMITTEE’S REVIEW AND PRIORITIES

To identify what is known and what is not known about potential impacts and about trends in industry practices related to impacts, the HEI Special Committee reviewed about 1,000 peer-reviewed articles and reports. Throughout its review, the Committee consulted with experts and stakeholders to develop this integrated assessment of research needs that spans the range of topics directly and indirectly related to potential impacts on health and well-being.

The Committee recognized that OGD can generate important benefits. Agencies and others at the regional, national, and international levels are actively engaged in the complex task of evaluating various combinations of energy sources, including a consideration of their ability to meet future energy requirements and climate-change potential. The Committee has sought to answer the more focused but critical question to help inform future energy policy choices: Which potential impacts of OGD warrant priority consideration for scientific study?

The Committee evaluated the potential for impacts from the following phases of OGD:

- Development (i.e., exploration, site preparation, vertical and horizontal drilling, hydraulic fracturing, well completion in preparation for production, and management of wastes);
- Production (i.e., extraction, gathering, processing, and compression of gas; extraction and processing of oil and natural gas condensates; management of produced water and other wastes; and construction and operation of pipelines); and
- Post-production (i.e., well closure and site reclamation).

The Committee's review did not include the following:

- Inter- and intra-state oil and gas distribution networks or other pipelines and compressor stations (beyond the gathering pipelines in the field) used to transport oil or gas outside of the production area;
- The end uses of oil and natural gas (e.g., electric power generation and vehicle fuel);
- The development and production of oil and natural gas from conventional geologic formations unless they involve the use of staged hydraulic fracturing combined with horizontal drilling; and
- Potential global climate-change impacts from OGD. The Committee reviewed information about climate-forcer emissions from OGD, but did not define research needs about the contribution of these emissions to global climate change, a research topic that is already the subject of extensive research programs around the world.

The Committee defined research questions based on a review of the literature and input received during expert consultations and two public workshops. The Committee also crafted seven criteria against which to identify and judge research areas. The criteria were intended to reflect the full breadth of research topics and characteristics that might be useful for understanding and preventing or minimizing potential impacts. In addition, the Committee identified several themes that pertain to multiple research questions (Table ES-1). Throughout its deliberations, the Committee stressed the need to account properly for these cross-cutting themes in research conducted in response to the Research Agenda. The research should also contribute to an improved understanding of these themes.

Guided by a review of the literature, input from stakeholders, and its own criteria, the Committee developed 35 research questions that cover the range of topics linked to the ultimate goal of understanding and preventing or minimizing potential impacts on human and ecological health and well-being. The Committee deemed all research questions to be important topics of inquiry, although not necessarily of equal importance.

Table ES-1. Cross-cutting themes that pertain to multiple research questions. These cross-cutting themes should be accounted for in studies designed in response to this Research Agenda. The research should contribute to an improved understanding of these themes.

Cross-Cutting Theme	Description
Background conditions	Many of the potential stressors associated with OGD have other sources: ▪ Natural sources (e.g., methane from biological sources or from depth by way of migration along natural fractures) ▪ Anthropogenic sources (e.g., conventional oil and natural gas development, orphaned and abandoned wells, active coal mines or abandoned mines, landfills, power plants, vehicle emissions, and long-range transport) Potential impacts attributed to OGD might have other causes: ▪ Baseline ecological characteristics and baseline human health and social characteristics must be distinguished from OGD-specific impacts.
Variability	Several factors related to levels of stressors and potential impacts can vary considerably: ▪ Spatial variability (e.g., geology, industry practice across regions, and location of OGD operations relative to surrounding communities and ecosystems) ▪ Temporal variability (e.g., changes to industry practice over time and duration of development) ▪ OGD facility variability (e.g., compressor stations and processing plants) ▪ Individual variability (e.g., human and ecological exposure and susceptibility)
Benefits of OGD	In some cases, the potential impacts of OGD could be interconnected with potential benefits. Some examples: ▪ Improvements to local infrastructure could decrease traffic injuries over the long term. ▪ Expansion of medical facilities in response to an influx of workers could improve access to healthcare.
Permitted, accidental, and unauthorized releases of stressors to the environment	Stressors entering the environment might lead to potential impacts: ▪ Stressors intentionally released in accordance with applicable regulations (e.g., permitted discharges to surface water, equipment emissions to ambient air, and vehicle emissions) ▪ Stressors released through illegal or poor practices (e.g., improper waste disposal or accidental releases of fracturing fluid and other materials)
Data availability and quality	Ready access to high-quality OGD-related data of various kinds (e.g., chemical usage, waste composition and management, and documentation of accidents) is essential to designing useful and efficient research. Some challenges to accessibility are the: ▪ Confidential nature of some information ▪ Lack of standard analytical methods for characterizing some OGD-related wastes ▪ Uneven documentation of some data Creation of standardized electronic (digital) reporting systems and databases would help facilitate ready access to OGD-related data. The Committee specifically noted the value of a standardized database to document permitted, accidental, and unauthorized releases from OGD operations.

The questions collectively indicate knowledge gaps; they are not findings of impacts. They are broadly applicable to Appalachia and other regions, although the importance of the questions likely varies by region. Comparative studies among regions would be useful in understanding how insights from one region might apply to other regions. Further, while the Committee's scope of review excluded OGD operations outside of the production area, the research questions are broadly relevant to OGD operations within and outside of production areas.

The research questions were defined relatively broadly to avoid pre-judging the specific type of research that could be performed. In this way, the Committee recognized that it does not have complete knowledge of every topic, nor can it anticipate new knowledge over the coming years. Research examples are provided for each question, but solely to aid the comprehension of the research questions.

The research questions fall into three general areas: (1) stressor and exposure characterization, (2) health and well-being assessment, and (3) evaluation of most-effective practices. The Committee recommends pursuing research in each of these areas. In particular, questions about stressor and exposure characterization are useful in addressing questions about health and well-being. Research on management practices can help prevent or reduce impacts in advance of waiting for the results of lengthy health studies.

Highlights of the Committee's Research Recommendations

35 Research Questions

- → They collectively indicate knowledge gaps; they are not findings of impacts.
- → They are linked to the ultimate goal of understanding and preventing or minimizing potential impacts on human and ecological health and well-being.
- → They apply broadly to Appalachia and other regions.
- → They fall into three general areas of research: (1) stressor and exposure characterization; (2) health and well-being assessment; and (3) evaluation of most-effective practices.
- → 13 questions are identified as high priorities, although all questions are important topics of inquiry.

Cross-cutting Research Themes

- → A number of themes should be accounted for in studies designed in response to this Research Agenda. These themes are:
    - o Background conditions (i.e., levels of stressors in the environment originating from natural and anthropogenic sources other than OGD, and baseline health characteristics that need to be distinguished from potential OGD effects)
    - o Variability with respect to a number of factors (e.g., geology, industry practice across regions and over time, and human and ecological exposure and susceptibility)
    - o Permitted, accidental, and unauthorized releases of stressors to the environment
    - o Benefits of OGD and their interrelationships with the impacts being studied
- → Research should contribute to an improved understanding of these cross-cutting themes.

Although the research questions cannot be pursued at the same time, they do not need to be carried out in a linear time frame. For example, all exposures do not need to be quantified before determining relationships between exposure and biological response (although both of these components are needed before quantitatively characterizing risks). However, health studies should be based on hypotheses about plausible links between OGD-related exposures and specific health outcomes. The individual research activities can be carried out in parallel and sequenced as needed to support effective analysis of exposures, risks, and health outcomes. In fact, such a parallel and sequenced execution will be crucial to achieve results in a timely fashion.

The Committee deemed all research questions to be important topics of inquiry, although not necessarily of equal importance. Funding for research to answer these questions, like that for all scientific research, is limited. The Committee therefore used its criteria to identify 13 research questions of "overarching importance," which target a better understanding of exposure, risk, and effects from a broad spatial and substantive perspective. Table ES-2 lists the topics in terms of three general areas of interest, the purpose of the research, and the topics of specific research questions — 13 of overarching importance and 22 other important topics. Table ES-3 provides brief descriptions of the topics addressed by the 13 research questions.

Table ES-2. The Committee's prioritized research questions by topic.

General Area of Research	Purpose	Research Topic (1)
Stressor and Exposure Characterization	To improve understanding of whether exposures of potential concern are occurring	**Topics of Overarching Importance (2)** ▪ Chemical toxicity (human and ecological) ▪ Emissions and air quality ▪ Total human exposure ▪ Water quality
		Other Important Topics ▪ Climate-forcer emissions ▪ Criteria air pollutants ▪ High-emitters ▪ Human biomonitoring ▪ Indoor air radon ▪ Induced seismicity causes ▪ Water use ▪ Water-quality diagnostics
Health and Well-Being Assessment	To improve understanding of whether potential impacts on public and worker health, ecological health, and well-being are occurring	**Topics of Overarching Importance (2)** ▪ Ecological health effects (landscape change) ▪ Public health effects (air exposure) ▪ Public health effects (near-term studies) ▪ Public health effects (water exposure) ▪ Social and psychosocial effects ▪ Worker health effects (chemical and radiation)
		Other Important Topics ▪ Community services and infrastructure ▪ Community well-being and health effect interactions ▪ Ecological health effects (chemical and radiation) ▪ Ecological health effects (cumulative) ▪ Public health effects (long-term studies) ▪ Public health effects (psychological stress) ▪ Worker health effects (noise, vibration, and physical hazards)
Evaluation of Most-Effective Practices	To enhance practices that minimize or prevent impacts	**Topics of Overarching Importance (2)** ▪ Accidental waste release ▪ Permitted waste management ▪ Wellbore integrity
		Other Important Topics ▪ Air quality control ▪ Community planning and resiliency ▪ Ecological health effects (mitigation) ▪ Induced seismicity prevention ▪ Water transport ▪ Wellbore diagnostics ▪ Workplace organization

(1) Within each category, research topics are listed in alphabetical order.

(2) The Committee identified 13 research questions of overarching importance, which target a better understanding of potential exposure, risk, and effects from a broad spatial and substantive perspective.

Table ES-3. Topics addressed by the 13 research questions of overarching importance (1).

Research Topic	Summary
Stressor and Exposure Characterization (2)	
Chemical toxicity (human and ecological)	Adequate toxicity information does not exist for some components of OGD fluids and wastewater. The initial goal of research would be to improve the understanding of the composition of these fluids. The goal of subsequent research would be to conduct toxicological evaluations where exposure information suggests that such evaluations would be helpful to decision-making about the protection of human and ecological health.
Emissions and air quality	OGD emissions might affect air quality. The goal of research would be to quantify the contribution of emissions from OGD to concentrations of a wide range of air pollutants.
Total human exposure	People might be exposed to a range of OGD-related health stressors, depending on the effectiveness of industry and regulatory protocols. The goal of research would be to identify these exposures and, for any of potential concern, to use rigorous methods to quantify them.
Water quality	Reports of surface water and groundwater contamination allegedly caused by OGD have garnered much public attention. The goal of research would be to quantify any contribution of OGD to short- and long-term trends in the quality of water resources.
Health and Well-Being Assessment (2)	
Ecological health effects (landscape change)	OGD can result in physical (e.g., habitat fragmentation) and sensory (e.g., increased light) changes to landscapes. The goal of research would be to quantify the contribution of OGD to short- and long-term landscape changes and any resulting ecological risks.
Public health effects (air exposure)	Emissions associated with OGD might lead to changes in air quality. The goal of research would be to determine whether variations in OGD-related airborne exposures are associated with health effects; these studies would focus on any quantified exposures of concern from high-quality studies of potential OGD impacts on air quality.
Public health effects (water exposure)	The scientific literature and popular press reflect concern about OGD-contaminated water resources. The goal of research would be to conduct population-based studies of health effects; these studies would focus on any quantified exposures of concern from high-quality studies of potential OGD impacts on water resources.
Public health effects (near-term studies)	Uncertainty about potential short- and long-term health effects related to OGD has led to community concern. The goal of research would be to determine, through systematic research, whether nearby communities are at increased risk for health effects that might be plausibly linked to OGD-related exposures. If an increased risk is identified, further research would then investigate in greater detail how and to what extent any such health effects are attributable to OGD-related stressors.
Social and psychosocial effects	OGD might have social and psychosocial impacts. The goal of research would be to determine whether and to what extent OGD might contribute to changes in individual and community well-being.
Worker health effects (chemical and radiation)	The OGD work environment can involve various health stressors, with exposure dependent on use of health and safety protocols. The goal of research would be to characterize and identify techniques for mitigating acute and chronic exposures of potential concern that are not already addressed by industry and regulatory protocols.
Evaluation of Most-Effective Practices (2)	
Accidental releases	OGD-related fluids and wastes can be released to the environment as a result of spills, leaks, blowouts, and other accidents. The goal of research would be to understand the nature of potential impacts from the accidental releases and how they might be prevented or reduced.
Permitted waste management	OGD generates solid and liquid wastes (e.g., produced water, drill cuttings, and drilling fluids). The goal of research would be to determine the potential for impacts from approved disposal of OGD wastes and the most-effective practices for managing the wastes.
Wellbore integrity	A tremendous amount of guidance exists to support the planning, design, and execution of well construction to prevent gas and fluids from escaping the wellbore. The goal of research would be to determine whether guidance is being broadly and effectively implemented and is sufficient to ensure the lifetime integrity of wellbores as OGD technology and practices evolve.

(1) The cross-cutting themes in Table ES-1 should be accounted for in studies designed in response to this Research Agenda. The research should contribute to an improved understanding of these themes.

(2) Within each category, research topics are listed in alphabetical order.

IMPLEMENTATION OF THE RESEARCH AGENDA

This Research Agenda is intended to identify opportunities for government, industry, nongovernmental organizations, and academics to work cooperatively toward improving the understanding of potential impacts and making further advances in minimizing or preventing them. The Committee anticipates that the Research Agenda will be used by researchers and those who fund them as well as by regulators, the oil and natural gas industry, environmental organizations, public health experts, and other stakeholders to inform policy development in this important area. It also serves as a framework within which existing research efforts fit.

High-quality research can be obtained in a number of ways. Given the complex and often controversial circumstances in which OGD is taking place, implementation of the Research Agenda will be most credible to a broad range of stakeholders if it is funded and overseen in a manner that leads to research of the highest quality, impartiality, and relevance. The success of the effort will depend strongly on cooperation among government, industry, and other stakeholders to create an environment of trust in which research can be conducted and the results can be relied on to support sound decision-making. This approach depends on four elements:

- Governance and Funding: Governance of the research program should be independent of its sponsors or other interested parties and be managed by an impartial research organization. Core funding should be balanced with sponsorship by industry, government, and possibly foundations and other sources. Ideally, funding should be provided for institutional and long-term support in the fulfillment of the Research Agenda outlined here and for other research topics and needs as they arise.
- High-Quality Science: The research should be overseen by a research committee and a review committee, each composed of leading scientists in various fields relevant to the Research Agenda. Members should be vetted to ensure that the research and review of results are carried out impartially. The research committee should competitively select studies for funding. The review committee, having no involvement in the selection, design, or oversight of the studies, should comprehensively review the studies for quality and technical rigor.
- No Advocacy: The mission of this independent research effort should be to produce the best science needed to make better informed decisions, without advocating policy positions.
- Communication: The research organization should communicate results widely and transparently, make the underlying data available, and disseminate comprehensive reports — including all results, both positive and negative — to the widest possible audience at no cost.

A key challenge, given the existence of numerous research questions in a period of potentially rapid growth in OGD, will be to ensure the prompt startup of the research program proposed here, with a strong emphasis throughout on streamlining every part of the program to provide the shortest possible turnaround in obtaining answers to the key questions to protect human and ecological health. The need for timely results would also argue for relying, as far as possible, on existing research organizations to expedite implementation.

The success of this comprehensive Research Agenda will depend strongly on the identification of significant and balanced funding and careful coordination with ongoing research efforts, such as the federal Multi-Agency Collaboration on Unconventional Oil and Gas Research and the National Institute of Environmental Health Sciences. The Committee recognizes, and would hope, that elements of this Research Agenda could be taken up as priorities for funding by appropriate agencies, e.g., the National Institute for Occupational Safety and Health (NIOSH) for worker health effects, and the Department of Energy National Energy Technology Laboratory (NETL) for wellbore integrity and other topics that overlap its research portfolio (National Energy Technology Laboratory 2015).

At the same time, a number of the overarching research questions would be best implemented as part of an integrated research program that could be pursued simultaneously. In pursuit of such an integrated program, certain groups of funders from both government and industry might choose to identify a major portion of this Research Agenda for funding, such as the overarching human exposure and health topics. Such funding can provide impetus to establish a new, integrated research program to specifically address those questions.

1. INTRODUCTION

Unconventional oil and natural gas development is a driving force behind significant economic and energy policy shifts in the United States and the world today. Technological advances in development are substantially increasing energy supplies, while at the same time outpacing the scientific research that can answer questions about the development's potential effects. With funding from private foundations, the Health Effects Institute (HEI)[1] convened a Special Scientific Committee to develop this impartial, multidisciplinary Strategic Research Agenda to help guide future research about potential adverse impacts[2] of 21st century oil and natural gas development. The result of the Committee's work is this Strategic Research Agenda. The Research Agenda recommends research to better understand and to prevent or minimize potential impacts on human health and well-being, communities, ecological health, and the environment. It was developed in response to questions raised in the Appalachian region of the United States. The questions are not unique to the region; therefore, the Research Agenda can address concerns expressed elsewhere in the United States and the world.

As used in this Research Agenda, "21st century oil and natural gas development" refers to the onshore development and production of oil and natural gas from unconventional geologic resources as practiced today, recognizing that industry practices continue to change in response to evolving technologies, regulations, and other factors. For simplicity, the term is abbreviated as "OGD" in this report.

The Committee has identified research that can address concerns expressed beyond Appalachia. For example, concerns about potential impacts on air quality and community change are widespread. Also widespread are reports of potential benefits, such as increased revenue flow to economically depressed areas and progress toward national energy security. Ideally, decisions about where and how oil and natural gas development occurs should be grounded in a scientific understanding of its potential impacts and benefits. Given its charge, however, the Committee focused on research that fills gaps in knowledge about potential impacts and that can support credible data-driven decision-making about understanding and preventing or minimizing any impacts. The Research Agenda can be used by researchers and those who fund them as well as by regulators, the oil and natural gas industry, environmental organizations, public health experts, and other stakeholders to inform policy development in this important area.

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[1] A list of abbreviations and other terms appears at the end of this agenda.

[2] Throughout this Research Agenda, the term "impact" refers to adverse effects. The term "benefit" refers to positive effects.

1.1 ORIGIN OF THIS INITIATIVE

In response to shale gas development in Appalachia, various organizations — each with its own specific focus — have acted to understand, prevent, and minimize potential impacts. One of these organizations was the Pennsylvania-based Shale Gas Roundtable, composed of leaders from government, industry, academia, environmental groups, and the public (*http://iop.pitt.edu/shalegas/*). The Roundtable was formed to answer one question:

> As a region, how can we most effectively and responsibly safeguard our communities and environment, grow our economy, and manage unconventional oil and gas development?

In its 2013 report, the Roundtable emphasized the need for "efforts to increase balanced research and rigorous monitoring of the possible impacts of unconventional oil and gas development." HEI's multidisciplinary Special Scientific Committee, which produced the Research Agenda presented here, was formed in response to this recommendation.

1.2 SCOPE OF THE COMMITTEE'S REVIEW

The Committee has sought to answer a critical question about development of oil and natural gas resources in the Appalachian Basin and beyond to help inform future energy policy choices: Which potential impacts of 21st century oil and natural gas development warrant priority consideration for scientific study?

1.2.1 What is 21st Century Oil and Natural Gas Development?

The Committee chose the term "21st century oil and natural gas development" instead of the more common "unconventional oil and natural gas development" to describe the subject of its review. This choice reflects the Committee's intent to address potential impacts of (1) oil and natural gas development that involves the use of staged hydraulic fracturing combined with horizontal drilling, which has been used in the Appalachian region since the development boom began; and (2) the possibility that these technologies will be used in the future with conventional geologic formations. (As noted earlier, "21st century oil and natural gas development" is abbreviated as OGD in this report.)

The Committee also considered the inherent difficulty of predicting the nature of oil and natural gas development in the decades ahead. Although future development can be envisioned to some extent (based on trends in industry practices, regulations, and the market), predictions about them do not provide a reasonable basis for identifying and prioritizing research needs. The Committee's recommendations for research, as presented in this Research Agenda, are therefore largely based on questions raised about practices today.

The extraction technique of staged hydraulic fracturing combined with horizontal drilling allows for the current wave of unconventional oil and natural gas development. Extraction, however, is only part of the oil and natural gas operations that have raised questions about potential impacts. The Committee therefore included the following phases of development in its definition of OGD:

- Development (i.e., exploration, site preparation, vertical and horizontal drilling, hydraulic fracturing, well completion in preparation for production, and management of wastes);
- Production (i.e., extraction, gathering, processing, and compression of gas; extraction and processing of oil and natural gas condensates; management of produced water and other wastes; and construction and operation of pipelines); and
- Post-production (i.e., well closure and site reclamation).

The Committee's review did not include the following:

- Inter- and intra-state oil and gas distribution networks or other pipelines and compressor stations (beyond the gathering pipelines in the field) used to transport oil or gas outside of the production area;
- The end uses of oil and natural gas (e.g., electric power generation and vehicle fuel);
- The development and production of oil and natural gas from conventional geologic formations unless they involve the use of staged hydraulic fracturing combined with horizontal drilling. This is not to say that the development of hundreds of thousands of earlier conventional wells in the Appalachian region is without potential impacts, but the widespread controversy today is associated with the use of these technologies. Potential impacts from the earlier development of conventional wells must be recognized in studies of the potential impacts of OGD, along with other contributors to background conditions. This issue is discussed further in Section 3.1; and

What do the terms "conventional" and "unconventional" mean in the oil and natural gas industry?

The terms "conventional" and "unconventional" are used widely in connection with the oil and natural gas industry but not consistently, creating confusion. Most people use them to distinguish between the geologic formations from which oil and natural gas are extracted. Others use them to classify how oil and natural gas wells are drilled today. Still others talk about them in the context of emerging oil and natural gas technologies and practices.

In the Agenda presented here, the Committee has used them to distinguish between geologic formations, as follows:

→ A *conventional formation* is one with relatively high permeability, in which the oil or natural gas has migrated to a natural reservoir and is held there by a rock unit that prevents further migration. When tapped, oil or natural gas from conventional formations flows readily into wellbores.

→ An *unconventional formation* is one with relatively low permeability (e.g., the Marcellus and Utica shales), in which the oil or natural gas does not flow readily into wellbores without the application of a well-stimulation technique, such as hydraulic fracturing.

Today, oil and natural gas are being extracted from wells drilled into both types of formations.

- Potential global climate change impacts from OGD. The Committee reviewed information about climate forcer emissions from OGD, but did not define research needs about the contribution of these emissions to global climate change, a research topic that is already the subject of extensive research programs around the world.

1.2.2 Weighing Benefits and Impacts

The Committee recognizes that oil and natural gas development can generate benefits at personal, 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. The benefits and impacts resulting from energy generation will hinge on the combination of energy sources actually used.

Governmental agencies and other organizations are actively engaged in the complex task of evaluating various combinations of energy sources, including a consideration of their ability to meet future energy requirements and climate-change potential. The Committee has sought to answer the more focused but critical question to help inform future energy policy choices: Which potential impacts of oil and natural gas development warrant priority consideration for scientific study?

Although the Committee’s charge was to define research needs related to potential impacts, the potential benefits also represent worthy topics of research that could be investigated in a separate research program. Such a program would extend beyond the questions that are presented here to include questions about socioeconomic, health, and political benefits. Even in the absence of such a research program, individuals and organizations conducting research on potential impacts should be mindful of possible interrelationships among benefits and impacts and account for them in studies designed in response to this Research Agenda.

Table 1-1 briefly summarizes some of the findings from recent reviews of potential local, regional, and national benefits of OGD that have been published in the peer-reviewed literature and other credible reports. In addition, OGD can bring benefits on a personal level, for example, to individuals with businesses that expand in response to the development and who receive lease payments. As is the case for potential impacts, the potential benefits are not distributed evenly among members of nearby communities. For example, someone who lives near an active well pad but does not own mineral rights might weigh the associated benefits and impacts differently than would a neighbor who is profiting from mineral rights. It is important to keep this heterogeneous distribution of both potential impacts and potential benefits in mind when reviewing Table 1-1.

1.2.3 Oil and Natural Gas Operations Under Review

This section provides a brief summary of the oil and natural gas operations that were the subject of the Committee’s review. Box 1 provides an overview of these operations along with an approximate average time required to develop and produce oil or natural gas from a single well with staged hydraulic fracturing combined with horizontal drilling. For a single well, the development phase (i.e., exploration, site preparation, drilling, and well completion) occurs over a period of months, although it could continue for a year or more in some cases, such as 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. The production phase usually continues for years to decades (Soeder et al. 2014).

Table 1-1. Examples of Potential Benefits from OGD (1)

Potential Benefit	Brief Description
Air quality or climate benefits from proportionally greater use of natural gas than coal or oil	With its lower point-of-use emissions, natural gas is generally considered to be a cleaner-burning fossil fuel than coal or oil. Therefore, the development of natural gas in the Appalachian region could yield air-quality benefits, depending on the extent of natural gas end use and emissions to the atmosphere during development, production, and distribution (Moore et al. 2014). Use of natural gas instead of other fossil fuels might benefit the climate, given its lower carbon emissions (Resources for the Future 2014).
Job creation	A number of studies have focused on job creation in the Appalachian region as a result of natural gas development (Considine 2010; Kelsey et al. 2011; Resources for the Future 2014).
Increased government revenues	Industry severance-tax payments (in West Virginia and Ohio) and impact fees (in Pennsylvania) have increased state revenue streams in areas experiencing development (Resources for the Future 2014). The amount of revenue that reaches local communities is uncertain, as most states designate these funds for general use or for use in oil and natural gas development and regulation (Resources for the Future 2014). The revenues could be used for other beneficial purposes, such as schools, parks, and social services.
Economic benefits for local communities	Information is limited, but retail activity in Pennsylvania might have increased as a result of development (Resources for the Future 2014). Local residents who lease their mineral rights are also likely to see an increase in income as a result of lease and royalty payments. Local taxes on earned income of residents and real property values and may benefit local governments and school districts in Pennsylvania (Environmental Law Institute and Washington and Jefferson College Center for Energy Policy and Management 2014).
National energy security	Multiple sources suggest that increased production from shale and other tight geologic formations has decreased U.S. reliance on foreign imports, leading to increased national energy security (American Petroleum Institute 2015; Mason et al. 2015a; Resources for the Future 2014). The U.S. Energy Information Administration (2015) projects that by 2017 the United States will be a net exporter of natural gas.
Supporting domestic manufacturing	Decreased natural gas prices have benefited industrial consumers, particularly in industries that rely on natural gas–driven processes (e.g., the chemical industry), and greater rates of gas production provide feedstock for chemical and manufacturing industries (Americal Chemistry Council 2014; Mason et al. 2015a).

(1) Potential benefits are heterogeneously distributed among individuals and communities. Potential benefits for some might lead to potential impacts for others. For example, a rise in housing costs might benefit property owners, but adversely affect renters.

Box 1. Timeline: Average duration of each phase in the life cycle of a well that is developed with staged hydraulic fracturing combined with horizontal drilling (1)

Re-stimulate (3)

Operational Phase	Activities	Time Required	
Exploration	Geophysical testing to determine target formation characteristics (e.g., depth and thickness) and geologic structures (e.g., fractures and faults) to support efficient siting of well pads and regional development of gas-support infrastructure.	1 to 2 months for field operation	Regionally (over 5 square miles), a three-dimensional survey takes a month or two. Locally (less than 5 square miles), a number of two-dimensional lines or a small three-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 for field operation	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	2 to 3 weeks	Depends on the depth of the topset, 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		Depends on the depth of the well, the length of the horizontal leg, the length and number of casings, and the amount of cement needed.
	Total drilling time if more than one well is installed on a single well pad	< 4 months	Actual time depends on the number of wells (assuming 8 wells per pad)
Well completion	Hydraulic fracturing of horizontal well	Weeks to ~ 1 month	A week or more to deliver and set up hydraulic fracturing equipment and 3 to 6 days per well to perform staged hydraulic fracturing. Pumping 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 technologic and economic factors.
	Preparing the well for production (or shut-in for later production)	Days to 4 weeks	Several days to a week to remove fracturing equipment, place production equipment and initiate production flush (flowback) of residual materials (i.e., proppant and other debris), and set the production equipment. This step can take longer if gas condensates or oil are produced along with natural gas, resulting in additional equipment needs related to processing and transmission.
Production	Extraction of oil and natural 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 natural 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 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 reclamation (can occur during production, depending on state law and local custom)	Indeterminate	Reclamation depends on the lease agreement and whether the site is to be maintained for future development.
Waste management	Storage, possible treatment and reuse, transport, and disposal of liquid and solid waste on or off the well pad	Years to decades	Weeks to months for wastes from drilling and hydraulic fracturing; years to decades for wastes from oil and natural gas production and processing, with quantities diminishing after the first months.

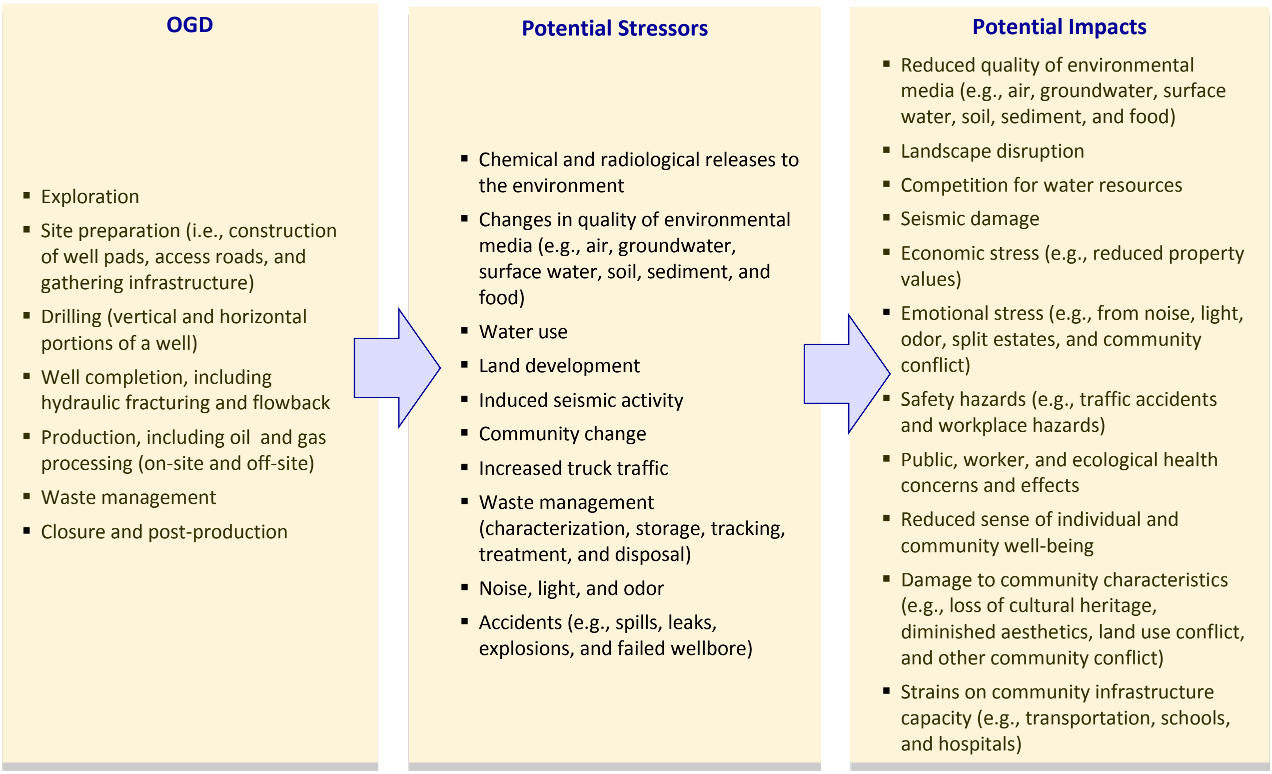
(1) Except where otherwise indicated, time estimates apply to development and production from a single well. In reality, well pads often contain multiple wells; therefore, the activity durations at a multiple well pad would exceed those reported here. The total time is not proportional to the number 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 time lapse between the original fracture and a potential refracture is typically measured in years and depends on the number of times that re-fracturing is technically and economically viable for each well.

1.2.4 Types of Potential Impacts Under Review

The Committee reviewed potential impacts that might affect human health and well-being, communities, ecological health, and the environment. The focus of the review was on OGD activities inside the Appalachian region, but consideration was given to generalizability and commonalities outside of the region. Figure 1-1 summarizes the scope of review, including OGD phases, the potential stressors resulting from them, and the potential impacts resulting from the stressors. Individual stressors might lead to multiple impacts. 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 community). The figure illustrates some of the relationships among oil and natural gas operations, potential stressors, and potential impacts. It provides examples rather than an exhaustive compilation of potential stressors and impacts.



OGD

- Exploration
- Site preparation (i.e., construction of well pads, access roads, and gathering infrastructure)
- Drilling (vertical and horizontal portions of a well)
- Well completion, including hydraulic fracturing and flowback
- Production, including oil and gas processing (on-site and off-site)
- Waste management
- Closure and post-production

Potential Stressors

- Chemical and radiological releases to the environment
- Changes in quality of environmental media (e.g., air, groundwater, surface water, soil, sediment, and food)
- Water use
- Land development
- Induced seismic activity
- Community change
- Increased truck traffic
- Waste management (characterization, storage, tracking, treatment, and disposal)
- Noise, light, and odor
- Accidents (e.g., spills, leaks, explosions, and failed wellbore)

Potential Impacts

- Reduced quality of environmental media (e.g., air, groundwater, surface water, soil, sediment, and food)
- Landscape disruption
- Competition for water resources
- Seismic damage
- Economic stress (e.g., reduced property values)
- Emotional stress (e.g., from noise, light, odor, split estates, and community conflict)
- Safety hazards (e.g., traffic accidents and workplace hazards)
- Public, worker, and ecological health concerns and effects
- Reduced sense of individual and community well-being
- Damage to community characteristics (e.g., loss of cultural heritage, diminished aesthetics, land use conflict, and other community conflict)
- Strains on community infrastructure capacity (e.g., transportation, schools, and hospitals)

Figure 1-1. The Committee's scope of review. (Left) The Committee reviewed potential stressors and impacts associated with the development, production, and post-production phases of OGD, including those at the well pad and beyond from ancillary facilities, such as processing plants, compressor stations, treatment facilities, and gathering infrastructure. The Committee's scope excluded inter- and intra-state distribution networks or other pipelines and compressor stations used to transport gas or oil outside of the production area. (Middle) Potential stressors are changes to the environment that might lead to impacts. (Right) Potential impacts are changes that might harm human health and well-being, communities near oil and natural gas development, ecological health, or the environment.

The Committee's evaluation of potential impacts on human health included consideration of both short- and long-term effects from exposure to one or more potential stressors associated with oil and natural gas development. These include, but are not limited to, potential chemical and radiation exposures through water, air, and soil; increased light, noise, and odors; and community changes. Stresses on regional resources and infrastructure were also considered. The evaluation of potential ecological impacts was similar to that conducted for human health impacts, except that it also involved consideration of habitat loss and fragmentation and changes in ecological community structure (i.e., the organization of and interaction among species that occupy a given area). The Committee also considered whether today's management of potential stressors and impacts is likely to prevent legacy impacts (meaning those that become apparent only after oil or natural gas production ceases).

1.3 EVOLUTION OF OIL AND NATURAL GAS DEVELOPMENT IN THE APPALACHIAN BASIN

The Appalachian Basin is a geologic structure extending from Alabama northward to New York. Oil and natural gas have been extracted from this structure 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, near Titusville, Pennsylvania, in 1859. Some controversy arose about environmental impacts in the late 1970s (e.g., 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 in the last several years, when hardly a day passes that a newspaper headline somewhere does not make reference to some aspect of oil and natural gas development, and specifically to hydraulic fracturing (Figure 1-2).

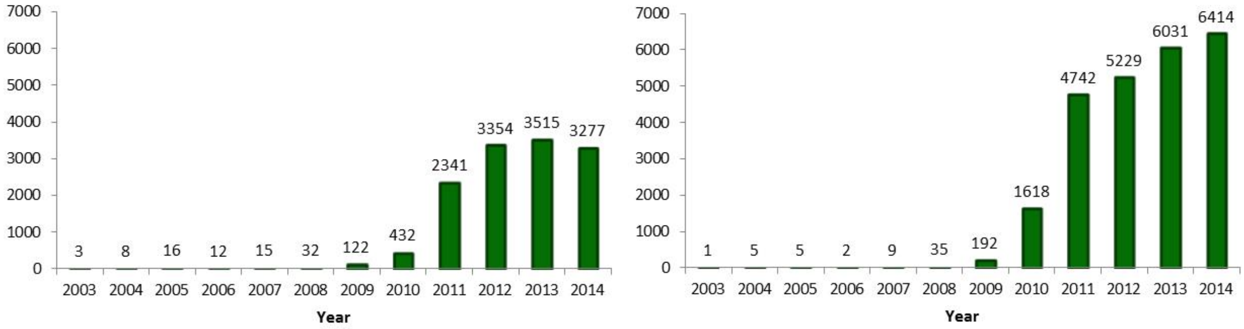


Figure 1-2. The number of news articles published each year between 2003 and 2014 with the terms (a) "hydraulic fracturing" and (b) "fracking" as reported by *Environmental Health News*. (Source of data: http://www.environmentalhealthnews.org/; accessed May 9, 2014.)

1.3.1 Historical Perspective

The Appalachian Basin's oil and natural gas resources have historically been extracted by drilling vertical wells into underground reservoirs, where trapped oil or natural gas then flowed readily into the well. The development of these conventional geologic 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 natural gas extraction 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; it has been used for decades in vertical wells in the Appalachian Basin. Hydraulic fracturing requires water or, less frequently, non-aqueous fluids alone or in combination with water (U.S. Environmental Protection Agency [EPA] 2015) mixed with proppants (e.g., sand or manmade materials to keep the cracks created by the hydraulic fracturing open) and smaller amounts of chemical additives.

Beginning in the 1980s and perhaps earlier for some resources, the initial development of unconventional geologic resources in the Appalachian Basin to extract coalbed methane gas and tight sandstone (“tight sand”) gas made use of hydraulic fracturing. The unconventional resources differ from conventional resources in that their lower permeability limits the flow of oil or natural gas into wellbores and requires well stimulation techniques (Figure 1-3).

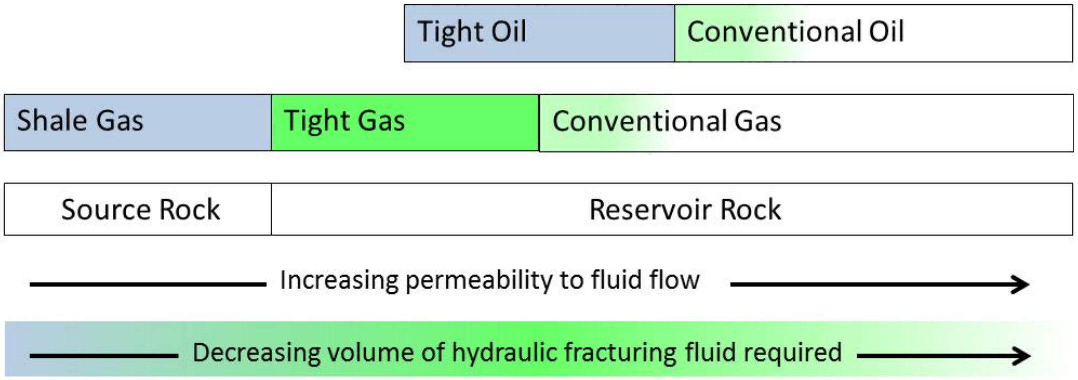


Figure 1-3. Relationship between the permeability of a geologic formation and the volume of hydraulic fracturing fluid required. The least permeable geologic formation is “source rock,” where the oil or natural gas was formed and has remained in place for millennia because of the rock’s low permeability. “Reservoir rock” includes a range of subsurface, porous rock bodies of various degrees of permeability in which oil, gas, or both can be found at some distance from the source rock. Well-stimulation methods have been used since the late 19th century to facilitate oil and natural 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 natural gas from various types of conventional and unconventional reservoir rocks. More recently, this technology has been used to extract oil and natural gas from source rocks, such as the Marcellus Shale. (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). Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.)

The oil and natural gas in these reservoirs originated from “source rock,” which is the geologic formation where it was originally formed. Even with the use of hydraulic fracturing to extract oil and natural gas from conventional and some unconventional formations, it was widely known that most of the oil and natural gas remains in the source rock, with no economically viable method of extracting it. The energy crises of the 1970s prompted research funded by the U.S. Department of Energy on these resources and hydraulic fracturing (Rodriguez and Soeder 2015); years of experimentation with horizontal drilling combined with hydraulic fracturing of unconventional formations yielded success in the Barnett Shale gas fields of Texas.

Staged hydraulic fracturing of wells with long horizontal segments differed from early hydraulic fracturing in conventional vertical wells in that it required millions instead of tens or hundreds of thousands of gallons of hydraulic fracturing fluid per well. The techniques of horizontal drilling combined with staged hydraulic fracturing (Box 2) 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 combined with staged hydraulic fracturing led to the widespread development of unconventional oil and natural gas fields such as the Barnett Shale, the Marcellus Shale, and the Bakken Shale (Pierobon 2013).

1.3.2 Contrasts Between OGD and Earlier Oil and Natural Gas Development

The techniques pioneered by Mitchell Energy for the successful extraction of natural gas from the Barnett Shale in Texas prompted similar and ongoing development of the natural gas–rich shale formations of the Appalachian Basin (Soeder 2012). Commercial production from unconventional gas wells began in 2005 in the Marcellus Shale (National Energy Technology Laboratory 2013) and in 2011 in the Utica Shale (Ohio Department of Natural Resources 2015). From these beginnings, development of the Marcellus and Utica shales as well as other resources has continued in Pennsylvania, Ohio, and West Virginia (Figure 1-4), with about 13,000 wells drilled between 2004 and March 2015 (Marcellus Center for Outreach and Research; *http://www.marcellus.psu.edu/resources/maps.php*).

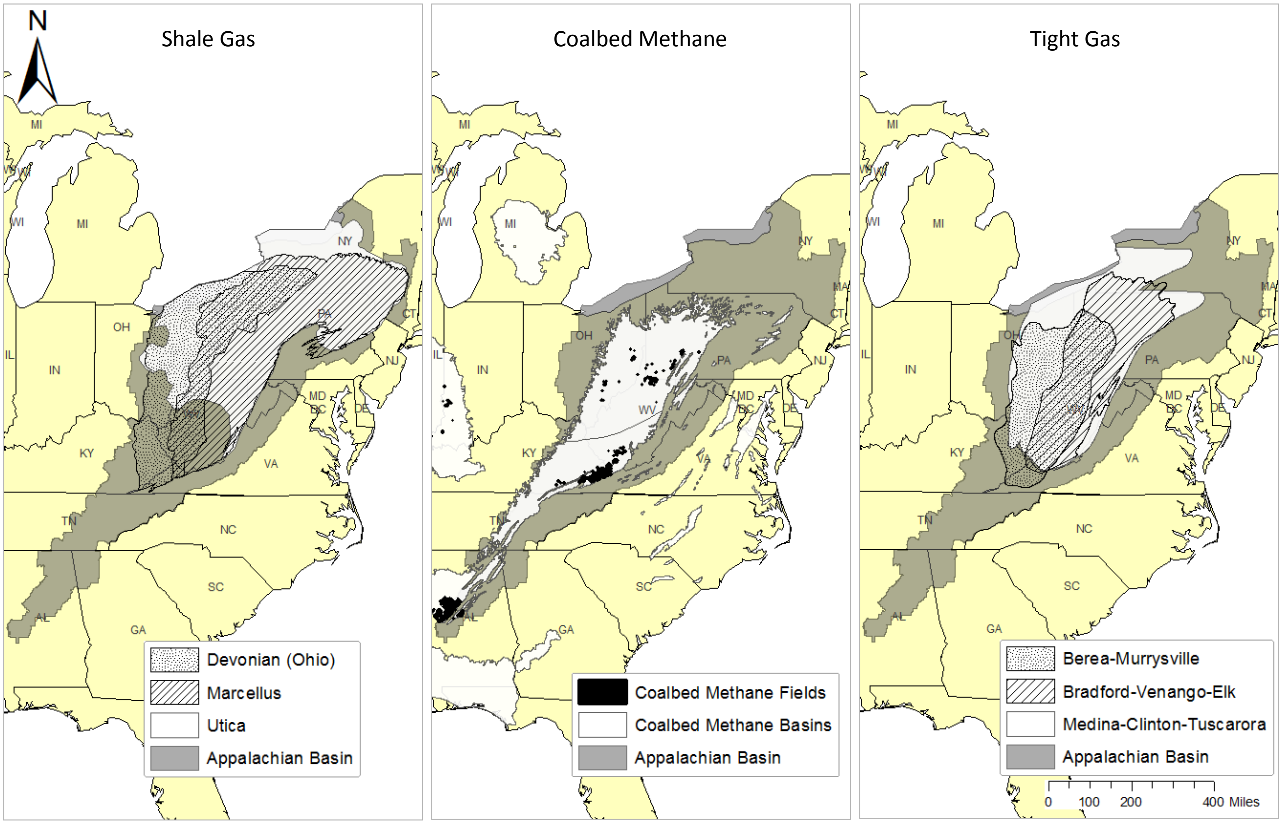
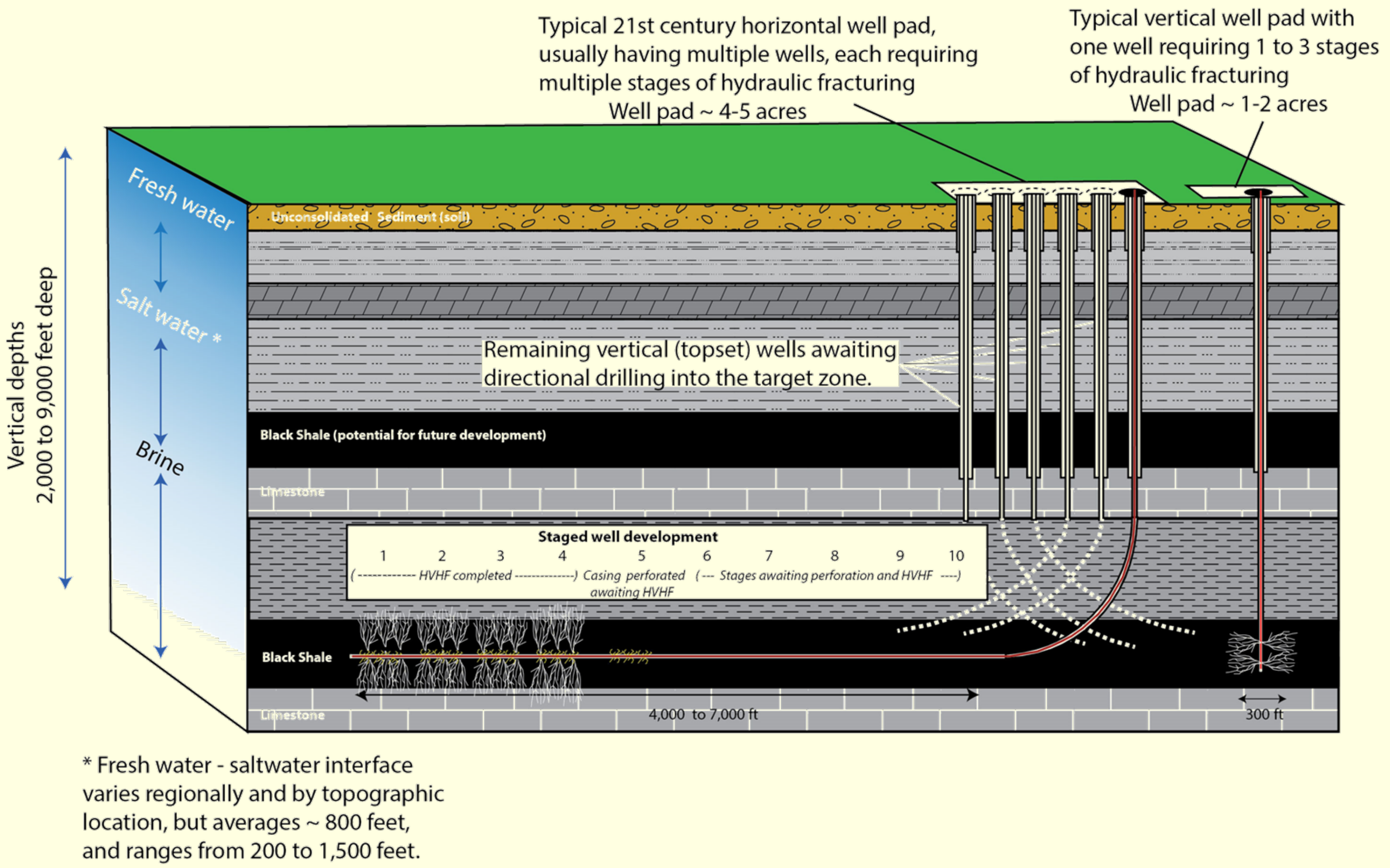


Figure 1-4. Extent of oil and natural gas resources in the Appalachian Basin. (Left) Shale "plays" (i.e., accumulations of shale gas) (data from 2011). (Middle) Coalbed methane fields and basins (data from 2006 and 2007, respectively). (Right) Tight-gas plays (data from 2010). (Source of data: U.S. Energy Information Administration 2014; *http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/maps/maps.htm*).

Box 2. What is new about oil and natural gas development in the 21st century?

Hydraulic fracturing, horizontal drilling, and extraction of oil and natural gas from unconventional formations, such as tight sandstone and shale, are not by themselves new. What is new is the use of staged hydraulic fracturing (typically requiring millions of gallons of water per well) combined with horizontal drilling (thousands of feet drilled within the target formation).This combination of technologic innovations has made previously uneconomical oil and natural gas resources productive enough to develop.



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 traditional well pad versus multiple horizontal wells on 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.)

What unconventional oil and natural gas resources are in the Appalachian Basin?

The Appalachian Basin includes several types of unconventional geologic formations, including shale, coalbeds, and tight sand.

Shale and tight sand are sources of oil or natural gas. Coalbeds are sources of natural gas.

The composition of natural gas varies and is often divided into two categories: “dry gas” and “wet gas.” Dry gas is formed under higher temperature and pressure conditions than wet gas and consists primarily of methane. Wet gas consists of methane mixed with ethane, butane, and other compounds commonly referred to as “natural gas liquids.”

Oil and natural gas development in the Appalachian Basin has historically involved conventional, and sometimes unconventional, geologic formations. Oil and natural gas were extracted from these formations either without hydraulic fracturing or with a form of hydraulic fracturing that required far less water. Figure 1-5 shows the active conventional and unconventional oil and natural 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 so much attention and controversy? These wells have a potential for different kinds of impacts.

The use of the new OGD processes began in 2004 in Pennsylvania and rapidly expanded to include eastern Ohio and northern West Virginia. Many people living in these regions were familiar with conventional oil and natural gas development, but not with the pace, scale, or type of the recent OGD (Figure 1-5).

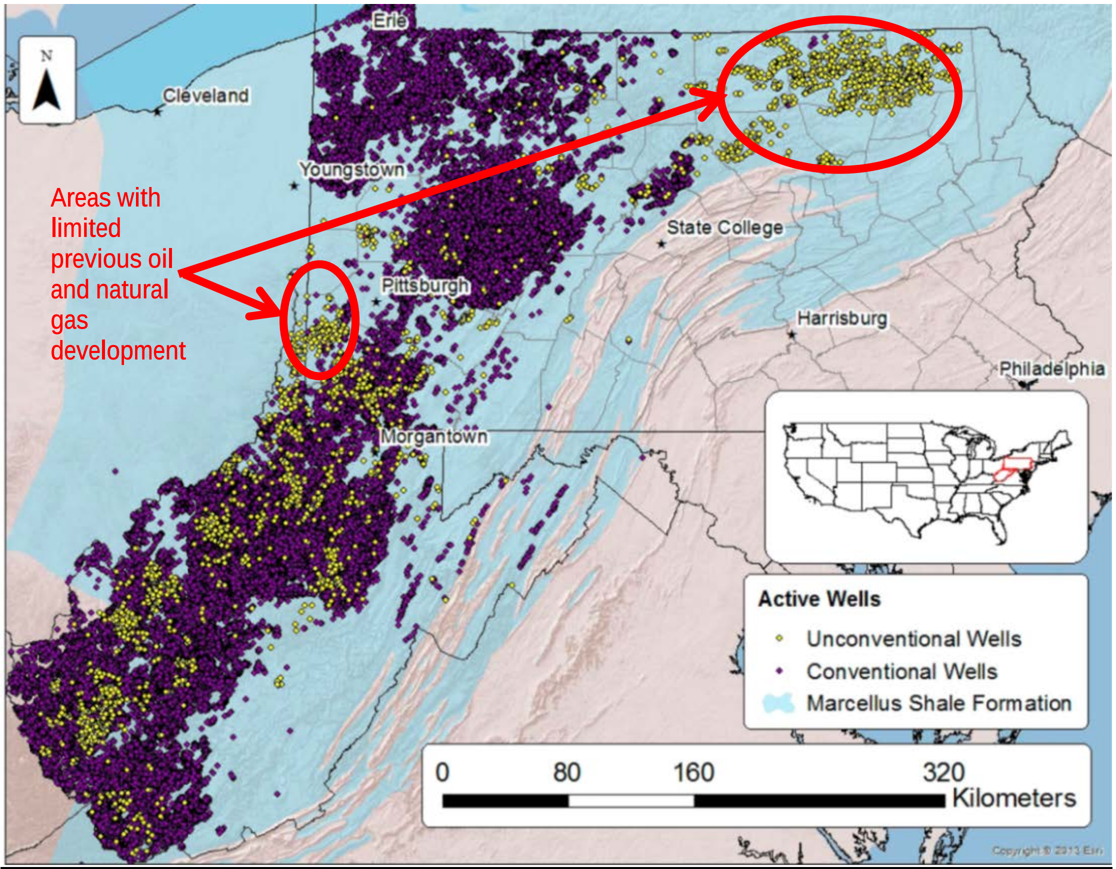


Figure 1-5. Active unconventional (yellow) and conventional (purple) oil and natural gas wells in Pennsylvania and West Virginia. (Reprinted with permission from Vengosh et al. 2014. Copyright 2014 American Chemical Society.)

The scale and pace of OGD has changed the dynamics of the world energy market. The evolving technology of staged hydraulic fracturing combined with horizontal drilling 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 for oil and natural 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 impacts now or by similar development near them in the future — have raised many questions about the potential impacts that this Research Agenda addresses.

Earlier extraction of conventional resources often involved short-term drilling with relatively small drill rigs (some mounted on a truck). In contrast, OGD involves larger rigs (as tall as 150 feet) and more equipment, supplies, and vehicles to support use of higher volumes of hydraulic fracturing fluid. These operations can occur around the clock and can involve many 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 (Rodriguez and Soeder 2015). In addition, new pipelines, compressor stations, and processing facilities must be constructed to support production and sometimes operate for decades.

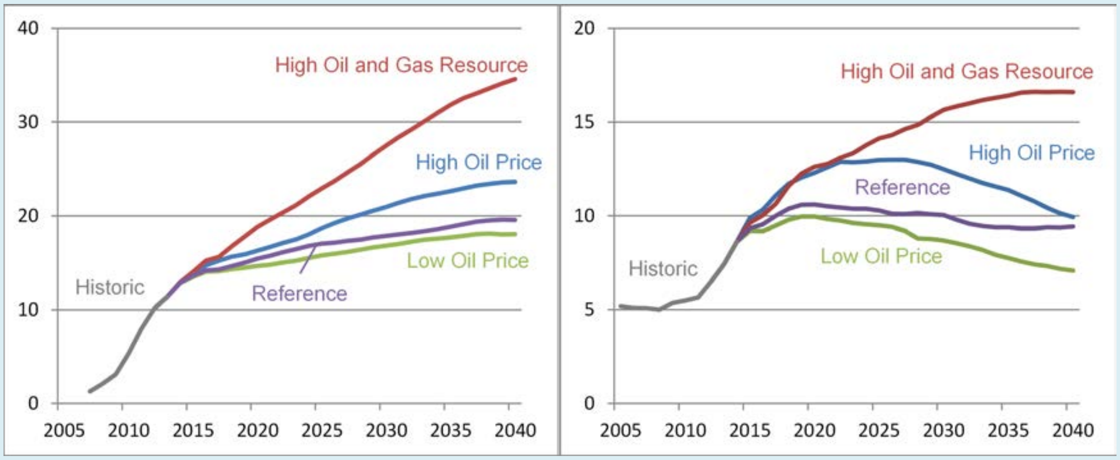
1.3.3 Anticipating the Future

The U.S. Energy Information Administration (2015) has predicted a continued rise in domestic natural gas production through 2040, with much of the increase being attributable to shale gas and tight gas from unconventional resources. The extent to which oil and natural gas will be produced depends on the viability of oil and natural gas resources, the future price of and demand for energy, and the regulatory and political environment. In addition, horizontal drilling and hydraulic fracturing technologies might be used in the future to improve production from conventional oil and natural gas resources throughout the Appalachian Basin and elsewhere in the United States.

Although it is not possible to predict the future of oil and natural gas development with any certainty, the Committee noted some trends in industry practices and the regulatory environment that are intended to address environmental and societal effects. For example, pipe networks have been replacing trucks for the transport of water. Also, much attention has been given to improving the management of liquid and solid wastes. Specifically, there is a trend away from storing wastewater in surface impoundments (which can pose a risk to wildlife and to groundwater if leaks form in the liner) to storing it in tanks (Rodriguez and Soeder 2015). Tanks are also subject to leaks and spills, but these are more easily detected and controlled than leaks from impoundments. In Pennsylvania, wastewater is no longer treated at publicly owned treatment works that were not designed to treat this type of wastewater. As of January 2015, West Virginia requires monitoring for the radiation content of waste deliveries to landfills (WV Code §22-15-8[h]). Some efforts have begun to coordinate innovative regulation among oil and natural gas-producing states, such as a collaboration of the Groundwater Protection Council and the Interstate Oil and Gas Compact Commission, called "States First." Also, STRONGER, Inc., a non-profit, multi-stakeholder educational organization, develops and shares guidelines for state oil and gas environmental regulatory programs and reviews volunteer state regulatory programs against the guidelines. In addition to regulation-related efforts, waste management and other industry practices are also being informed by new and evolving guidance from organizations such as the American Petroleum Insitute and the Center for Sustainable Shale Development and by technological innovations (e.g., research performed and funded by the Environmentally Friendly Drilling) that are intended to minimize adverse environmental impacts and ensure safe development. Some organizations are documenting evolving practices in searchable databases, such as the Intermountain Oil and Gas Project at the University of Colorado (http://www.oilandgasbmps.org). These are just a few examples of the changes in the oil and natural gas industry and the regulatory environment that will influence whether and how impacts might occur.

The future of crude oil and shale gas production in the United States

The U.S. Energy Information Administration (EIA) has predicted a continued rise in domestic shale gas and crude oil production through 2040 under specific pricing assumptions. In the EIA Reference case, over 50% of the total increase in shale gas production over EIA's projection period originates from the Haynesville and Marcellus geologic formations.



U.S. shale gas production in four cases, 2005-40 (trillion cubic feet)

U.S. total crude oil production in four cases, 2005-40 (million barrels per day)

(Source: U.S. Energy Information Administration 2015)

1.4 RESEARCH RECOMMENDATIONS FROM OTHER ORGANIZATIONS

Other organizations have identified the need for more study of potential impacts and have offered their own research recommendations. Appendix A summarizes recent recommendations gathered from peer-reviewed scientific literature and reports from nongovernmental research organizations, industry, and government agencies as of August 2015. The recommendations apply to a broad range of topics that fall within the Committee's charge; the Committee therefore considered these recommendations in conjunction with its own review of the literature when formulating this Research Agenda. The success of this Research Agenda will depend strongly on careful coordination with ongoing research efforts (see Section 5).

2. METHODS

This section describes the Committee's approach to (1) identifying potential impacts, (2) formulating questions designed to guide research whose findings will help fill gaps in knowledge about the potential impacts, and (3) identifying the questions that should be given higher priority for research.

2.1 IDENTIFICATION OF POTENTIAL IMPACTS

The Committee's review of the potential impacts consisted of the following:

- An extensive literature review,
- Consultations with experts, and
- Consultations with stakeholders.

The Committee reviewed about 1,000 articles and reports (see Appendix B) focused on information related to potential impacts rather than the enormous and important literature about the technology underlying OGD. Some of the articles and reports are directly related to OGD in the Appalachian Basin; others provided information about OGD elsewhere that might be relevant to the Appalachian Basin. In its review, the Committee gave priority to peer-reviewed articles from the scientific literature as well as to reports and data from nongovernmental research institutions and government agencies with knowledge of and expertise about oil and natural gas development and production in the Appalachian region. As noted earlier, findings from some of the current literature might not be relevant to future development conditions, given the changes in oil and natural gas industry practices and the regulation of the industry. However, the findings might be important for understanding earlier and potentially long-lasting impacts of past and current practices.

Committee members brought relevant knowledge and experience to their research planning, with expertise in many disciplines ranging from geophysics and petroleum geology to epidemiology, medicine, aquatic ecology, and sociology (See Appendix E). Nevertheless, the Committee consulted additional subject-matter experts to develop a deeper understanding of current industry practices. Through in-person meetings, webinars, and well pad tours, experts briefed the Committee on unconventional oil and natural gas geology and industry practices in the Appalachian Basin and on trends in industry practices, particularly fracturing methods.

The Committee summarized its review of potential impacts in a draft interim report released in December 2014 and has continued to review the literature published since that time. The Committee's updated summary review of the literature regarding potential impacts of OGD is in Appendix C. The discussion of the literature presented in the appendix is subject to change as the literature on potential impacts develops and as industry practices and technology continue to evolve. In some cases, industry practices have changed to prevent or reduce impacts.

Communication with stakeholders was clear and consistent throughout the Committee's research planning. HEI conducted two public workshops to present the Committee's work and to provide opportunities for constructive discussion among various interest groups about the potential impacts, research questions, and criteria for prioritizing research questions. This Research Agenda underwent peer review and was the topic of a third workshop, which provided another opportunity for stakeholder input, specifically on how the committee used the information received during earlier workshops to prepare this Research Agenda.

2.2 FORMULATION AND PRIORITIZATION OF RESEARCH QUESTIONS

The Committee's formulation and prioritization of research questions was guided by its review of potential impacts as described in Section 2.1 and by criteria that it developed.

2.2.1 Formulation

The Committee developed seven criteria, listed in alphabetical order in Table 2-1, based on an initial broad review of the literature and recommendations from public workshop participants. The criteria were intended to reflect the full breadth of research topics and characteristics that might be useful for understanding and preventing or minimizing potential impacts of OGD.

As reflected in its criteria, Committee members assessed research that addressed important potential impacts of broad geographic applicability yet also recognized practical considerations such as time sensitivity, feasibility, and utility for decision-making and planning. The Committee also looked at a variety of ways to identify research valued by local communities (e.g., Brasier et al. 2011; Korfmacher et al. 2014; Perry 2013; Powers et al. 2015; Schafft et al. 2014; Siikamäki and Krupnick 2013). The Committee's criteria were qualitative and, consequently, were used to make a qualitative rather than quantitative assessment of potential topics of scientific inquiry. The goal was to define a research agenda that, when implemented, would provide the knowledge needed to answer the most important questions about the potential impacts of OGD.

Each research question is accompanied by a brief description of its technical basis and some examples of the type of research to address it. The Committee defined research questions relatively broadly to avoid prejudging the specific types of research that could be performed, recognizing that it did not have complete knowledge of every topic and could not anticipate new knowledge over the coming years. The research examples, therefore, are provided solely to aid the comprehension of the research questions.

The research questions focus on work designed to help understand and prevent or minimize potential exposures and impacts that are specific to OGD. The Committee was mindful of ongoing relevant scientific research; however, it did not refrain from recommending similar research, because the ongoing work is not yet complete, and its full scope and quality cannot be known at this time. Implementation of this Research Agenda should be coordinated with ongoing research programs to attain answers as quickly and as efficiently as possible.

Table 2-1. Criteria for formulating and evaluating research questions.

Criterion	Description
Capacity to directly inform decision-making and planning	Is the research related to decisions or plans being made now or in the next few years? Could additional data resulting from the research affect these decisions or plans? Can the data be published (or at least be peer-reviewed) in time to inform the decisions or plans?
	Can the research help evaluate oil and natural gas industry practices and identify most-effective practices? Can it help inform decision-making, planning, or regulation related to the industry?
Feasibility	Can the research be implemented with relative ease (e.g., are relatively well-established tools and techniques available or are field research locations readily accessible)?
	Is the research question ripe for study; that is, have the knowledge and understanding of the subject matter matured to a degree that the research is likely to yield relevant and robust quantitative or qualitative data?
	Does the research allow for the detection of possible causal links between exposures or impacts and one or more aspects of oil and natural gas development?
	Can the desired data be obtained efficiently, or will disproportionate amounts of time, money, or effort be expended in pursuing the research?
Geographic applicability	Is the research designed to produce results that apply broadly to the Appalachian region?
	Is the research designed to produce results that also apply to other regions of the United States or elsewhere?
Scope of the research	Does pursuing the research contribute to the understanding of multiple exposures or impacts?
Significance of potential impacts	Are the exposures or impacts relevant to large geographic areas, large populations, or large or multiple ecosystems?
	Is the severity of the potential impacts likely to be large, regardless of the size of the affected geographic area, human population, or ecosystem? The severity of an impact is a function of the frequency, duration, and magnitude of exposure to a stressor as well as the harmful properties of the stressor.
	Do any qualitative characteristics (e.g., irreversibility, uncontrollability, unfamiliarity, or uneven distribution over space, time, or populations) of the exposures or impacts raise additional concern?
Time sensitivity	Are the impacts occurring now or anticipated in the near future? Could data resulting from the research be used to protect against potential impacts?
	Should the research be initiated in the near term to help ensure better assessment of potential impacts over the medium and long term?
Value to local communities	Has the research topic been identified as important to people living in communities near oil and natural gas development?

2.2.2 Prioritization

The Committee deemed all research questions to be useful topics of inquiry, although not necessarily of equal importance. The Committee proceeded through several iterations of using its criteria to rank the research questions. After each iteration, the committee applied what it learned to revise the criteria and priorities. These criteria reflect the outcome of the Committee’s evolving views of the research question attributes that were most critical for setting the priorities. Recognizing that funding is finite, the Committee used these refined criteria to identify research questions of overarching importance.

3.0 RESEARCH QUESTIONS

Based on its review of the literature (Appendices B and C), input received during its three public workshops to date, and its criteria, the Committee carefully considered what is known and not known about potential impacts of OGD and formulated 35 research questions designed to fill important knowledge gaps (Table 3-1). This section summarizes the context and motivation for each research question and identifies example research activities. It begins with a brief summary of cross-cutting themes that are relevant to the research questions. The research questions are then presented by topic rather than by priority. Research questions about health and well-being are presented last simply because their answers will rest, in part, on answers to the preceding research questions.

A great deal of research is already under way, as are important efforts to compile existing data and information into frameworks useful for decision-making. The Committee strongly encourages use of this ongoing work to efficiently attain answers to the research questions.

3.1 CROSS-CUTTING THEMES

The Committee noted several themes that pertain to multiple research questions presented in Sections 3.2 through 3.9. Throughout its deliberations, the Committee stressed the need to account for these themes in research conducted in response to the Research Agenda. Ideally, research would also contribute to an improved understanding of the themes.

3.1.1 Background Conditions

Many of the potential stressors and impacts associated with OGD also have natural sources (e.g., methane from biological sources or from depth by way of migration along natural fractures) and other anthropogenic sources (e.g., conventional oil and natural gas development, orphaned and abandoned wells, active coal mines or abandoned mines, landfills, power plants, vehicle emissions, and long-range transport). Study designs must recognize and accommodate this reality to support conclusions about the source of potential impacts.

Potential impacts attributed to OGD might have other causes, depending on the baseline ecological characteristics and baseline human health and social characteristics in geographic areas near OGD-activities. These baseline characteristics, including any changes in them over time, must be distinguished from potential OGD-specific impacts.

3.1.2 Spatial Variability

The type, location, and extent of OGD vary as a result of factors that are distributed spatially. These factors include geology, hydrology, meteorology, distance from communities and ecosystems, regulatory requirements, and industry practice. This spatial variability, in turn, influences the potential for the release of stressors to the environment and whether potential impacts might follow. For example, the composition of hydraulic fracturing fluid and produced water can vary depending on geologic conditions, which in turn influences the type of exposures that can occur.

In this report the Committee has focused on the Appalachian region, but many of its research questions are relevant to other regions. The Committee stressed throughout its deliberations that future study designs must recognize, account for, and improve understanding of spatial variability. Doing so is critical to proper interpretation of study results and ultimately their generalizability. Comparative studies among regions would be useful in understanding how insights from one region might apply to other regions.

3.1.3 Temporal Variability

Some of the factors that influence spatial variability in potential stressors and impacts (e.g., variation in regulatory requirements, market conditions, and industry practice) also influence their distribution over time. Changes over time cannot be predicted with certainty, but questions that could help develop insight include the following:

- How does the potential for impacts vary over the lifetime of a well?
- How might modifications in industry practices over time reduce or increase the likelihood or possibility of impacts (e.g., chemical substitution to reduce the potential for human or ecological toxicity)?
- How might existing and newly collected data relevant to stressor releases be made available for research and policy action?
- How long will development last in the region and what scale of development might occur? Is it possible that, as in some locations in Colorado, 30 wells could be drilled on a single well pad in Appalachia? Might development of coalbed methane or other types of resources become more prevalent and bring with it unique impacts that are not apparent at this time?
- How does today’s management of potential stressors and impacts from OGD compare to historical practices? Are today’s most-effective practices, whether initiated by industry or required by regulation, sufficient to prevent legacy impacts?

3.1.4 Individual Variability

Both exposures and biological responses to exposures are unevenly distributed across individuals in human and ecological populations. Variability in exposures and responses must be acknowledged and addressed in future research. The need to quantify exposure variability influences many study design elements, including, for example, the number, type, and location of sampling devices and the averaging time and frequency of sampling programs. Ideally, study populations would be representative in terms of variability in exposure and susceptibility and include those who are likely to be most highly exposed and also most vulnerable to the effects of the specific potential health stressor under investigation.

3.1.5 OGD Facility Variability

Individual wells and associated facilities, such as compressor stations and processing plants, have their own unique character, stemming from their location, design, and stochastic nature of facility operations. Although exhaustively studying a single facility can be informative, investigators must be very careful about expecting to get answers that apply to many. This variability is a core challenge for many of the OGD research topic areas (e.g., air quality, water quality, and wellbore integrity).

3.1.6 Benefits of OGD

Potential benefits of OGD might be related to potential impacts of OGD such that they warrant consideration in research conducted in response to this Research Agenda. For example, improvement of roadways and traffic control systems in response to OGD might lead to improved traffic safety over the long term. Similarly, overall quality of health care and, as a result, community health might be enhanced if monitoring and treatment infrastructure are improved. Higher rates of employment might lead to greater access to health care coverage. Such coverage should lead to improved health in the long term or to an increase in the incidence of specific neglected health conditions. In the short term it might lead to an apparent increase in the reported incidence of specific neglected health conditions. Thus it will be important in prospective research to distinguish increased rates of specific health conditions due to adverse impacts of OGD from increased rates that are an artifact of increased access to healthcare or other potential benefits of OGD.

3.1.7 Permitted, Accidental, and Unauthorized Releases of Stressors to the Environment

Some stressors are released to the environment in accordance with applicable regulations (e.g., permitted discharges to surface water, equipment emissions to ambient air, and vehicle emissions). Unfortunately, some stressors are released as a result of poor practices (e.g., improper waste disposal, accidental releases, and explosions) or unauthorized activities (e.g., illegal disposal of waste materials). Records are available to document and study legal releases. Records are also available for known illegal releases in the form of regulatory violation notices. These records have been mined to assess the potential for impacts (e.g., Brantley et al. 2014). OGD practices and regulations continue to evolve, and additional and more expansive record reviews might prove useful in understanding and assessing potential impacts. A rigorous multivariate analysis of the data about events involving accidental or unauthorized releases might detect patterns that could guide the continued evolution of practices to prevent, detect, contain, and remedy such releases.

Section 3.5 discusses recommendations specific to releases related to waste management and lists various organizations already working to organize data and information relevant to understanding the potential for all kinds of releases to the environment.

3.1.8 Data Availability and Quality

Ready access to high-quality OGD-related data of various kinds (e.g., chemical usage, waste composition and management, and documentation of accidents) is essential to designing useful and efficient research. Some challenges to accessibility are the confidential nature of some information, the lack of standard analytical methods for characterizing some OGD-related wastes, and the uneven documentation of some data. Creation of standardized electronic (digital) reporting systems and databases would help facilitate ready access to OGD-related data, with some efforts under way already. Examples include the FracFocus public database with reported chemicals used for hydraulic fracturing, which is managed by the Ground Water Protection Council and Interstate Oil and Gas Compact Commission; and the Risk Based Data Management System for tracking protection activities related to oil and gas development, which is managed by the Groundwater Protection Council.

The Committee specifically noted the value of a standardized electronic database to document permitted, accidental, and unauthorized releases from OGD operations. Collaborations among industry, regulatory agencies, organizations creating relevant databases, and database users would be critical to (1) make the best possible use of existing reporting systems; (2) define a practical and flexible system; (3) document data quality for use in understanding potential impacts; and 4) maintain the database such that it provides accessible and easily searchable data.

Table 3-1. The 35 research questions.

Topic Area (Section #)	Research Topic	Research Question
Wellbore Integrity (3.2)	Wellbore integrity	Is guidance for ensuring lifetime integrity of OGD wellbores broadly and effectively implemented? Is available guidance sufficient to ensure lifetime integrity of OGD wellbores?
	Wellbore diagnostics	What tools and techniques can be developed to better assess wellbore integrity? How does wellbore integrity change over time?
Air Quality (3.3)	Emissions and air quality	What are the effects of OGD on air pollutant concentrations?
	Criteria air pollutants	To what extent does OGD affect concentrations of ozone and $PM_{2.5}$?
	High-emitters	What is the effect of high-emitters on air quality? How can high-emitters' emissions be identified and resolved?
	Climate-forcer emissions	What are the OGD emissions of methane and other climate-forcing pollutants?
	Air quality control	How effective are current and emerging OGD air-emission control and prevention technologies and practices?
	Indoor air radon	Does OGD increase indoor air concentrations of radon?
Water Quality and Use (3.4)	Water quality	What are the surface water and groundwater quality conditions before, during, and after OGD?
	Water use	What water-use requirements are needed to protect ecosystems affected by OGD? How does local hydrology affect water use? How will new reuse or recycling technologies affect future water demand ?
	Water quality diagnostics	What are the sources of water contamination potentially related to OGD, and how can they be identified or distinguished?
	Water transport	What are the advantages and disadvantages of the various means of supplying water to and transporting wastewater from OGD well pads for off-site management?
Waste Management (3.5)	Accidental waste release	What are the frequency and characteristics of accidental releases of OGD solid and liquid waste? How can collection and sharing of data documenting these releases be improved? How can the regional extent of the plume of pollutant released be identified?
	Permitted waste management	What are the potential impacts from permitted practices for managing OGD solid and liquid waste? What are the most-effective practices for managing wastes from OGD?

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Table 3-1. The 35 research questions.

Topic Area (Section #)	Research Topic	Research Question
Induced Seismicity (3.6)	Induced seismicity causes	What geologic conditions and engineering practices contribute to induced seismicity?
	Induced seismicity prevention	What predictive methods and preventive practices are most effective in mitigating induced seismicity caused by disposal of OGD wastewater in underground injection control wells?
Chemical Toxicity (3.7)	Chemical toxicity (human and ecological)	What are the composition and toxicity of chemical mixtures unique to OGD and how can their toxicities be determined? How does toxicity change over time due to microbe–water–rock interactions in reservoirs over the lifetime of the well?
Ecological Health (3.8)	Ecological health effects (landscape change)	Do the short- and long-term landscape changes associated with OGD affect terrestrial and aquatic habitats and present risks to ecological health?
	Ecological health effects (chemical and radiation)	Are there chemical and radioactive ecological exposures that result from OGD and acute or chronic ecological health risks associated with these exposures?
Ecological Health (3.8)	Ecological health effects (cumulative)	Are there important additional risks that result from cumulative exposure to multiple ecological health stressors (e.g., physical, sensory, radioactive, or chemical) associated with OGD?
	Ecological health effects (mitigation)	What practices are most effective for mitigating OGD-related physical and chemical stressors that might contribute to ecological impacts? Do these practices protect the most vulnerable ecological elements?
Human Exposure and Health Risk Assessment (3.9.1)	Total human exposure	How can total human exposures to OGD stressors be estimated? What exposure pathways and phases of OGD should be considered in estimating the exposure?
	Human biomonitoring	Are there biomarkers of exposure that are useful for understanding total exposure to OGD-related health stressors? Are there biomarkers that reflect health risks (e.g., chronic inflammation, DNA damage, and oxidative stress) specific to OGD?
Worker Health (3.9.2)	Worker health effects (chemical and radiation)	Under what conditions and to what extent are OGD workers exposed to chemical or radioactive health stressors? Do these exposures lead to health effects?
	Worker health effects (sensory and accidents)	Under what conditions and to what extent are OGD workers exposed to chronic sensory (e.g., noise and vibration) or acute physical hazards (e.g., vehicular accidents, falls, and burns)? What are the acute traumatic consequences? What are the chronic disease consequences (e.g., hearing loss)?
	Workplace organization	How do workplace organization and culture affect the health and safety of OGD workers? How can industry leadership identify, select, and measure the effectiveness of interventions that can help reduce or prevent threats to worker safety and health?

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Table 3-1. The 35 research questions.

Topic Area (Section #)	Research Topic	Research Question
Public Health (3.9.3)	Public health effects (near-term studies)	Are there demonstrable increases in symptom reporting, illnesses, doctor visits, accidents, or hospitalizations among community members living near OGD? Are any such indicators of health effects attributable, singly or in combination, to specific chemical, physical, or sensory stressors associated with OGD?
	Public health effects (water exposure)	Are there health effects associated with measurable OGD-related exposures in water resources?
	Public health effects (air exposure)	Are there health effects associated with measurable OGD-related exposures in air, including unusually high short-term exposures?
	Public health effects (psychological stress)	Do psychological stressors associated with OGD affect the health of individuals in affected communities?
	Public health effects (long-term studies)	Are there long-term mental or physical health effects resulting from short-term or chronic exposures to chemical or physical stressors associated with OGD?
Individual and Community Well-Being (3.9.4)	Social and psychosocial effects	How do impacts of OGD on community-level social and psychosocial conditions vary in relation to the level and phase of development, proximity to development, land use, resource ownership, and the unique sociocultural contexts of communities?
	Community services and infrastructure	What are the impacts of OGD on community-level infrastructure and public and private-sector service provision? How do such impacts vary in relation to the level and phase of development, proximity to development, and specific community characteristics (e.g., population size, location in relation to surrounding communities, and areas of population concentration)?
	Community planning and resiliency	How can communities better anticipate, prepare for, adapt to, and respond effectively to growth effects and other impacts of OGD?
	Community well-being and health effect interactions	In what ways and to what extent are community-level social and psychosocial impacts of OGD associated with physical and mental health consequences and increased use of medical and mental health services?

3.2 WELLBORE INTEGRITY

Careful planning, design, and execution of well construction are essential to prevent gas and fluid from escaping the wellbore and reaching sensitive resources, such as shallow aquifers with potable water.

Topic:	**Wellbore integrity**
Question:	**Is guidance for ensuring lifetime integrity of OGD wellbores broadly and effectively implemented? Is available guidance sufficient to ensure lifetime integrity of OGD wellbores?**

Background: Wellbore integrity means that gas and fluid from outside or inside (e.g., injected or produced fluid) the wellbore do not unintentionally enter or migrate from one point to another along the wellbore, especially into drinking water aquifers or the atmosphere. The design, drilling, completion, production, and closure of a well must be performed in accordance with applicable regulations and most-effective engineering practices, such as applicable guidance from the American Petroleum Institute (API). These practices include selection and use of optimal drilling fluids, steel casing types, and cements as well as proper training, supervision, and coordination of company and contract personnel. Wellbore failures can result in gases or liquids leaking into aquifers or the air (e.g., EPA 2015; Davies et al. 2014).

Key practices that ensure wellbore integrity during and after well construction include the following:

- Use of cement formulated for the specific job (e.g., Crain 2000; API Recommended Practice [RP] 10A/ISO 10426);
- Proper cement preparation, using appropriate mix water and minimizing free water separation (API RP 65-2);
- Use of drill bits and casings properly sized (API RP 65-2) to allow for adequate cement flow (e.g., no big casings in small holes);
- Inspection of welds on well casing and use of equipment to properly makeup threaded connections to the recommended torque (API RP 5B and 5C1);
- Selection of equipment and fluids designed for optimal cleaning of mud from the spaces between casings and borehole walls (i.e., annular spaces);
- Use of centralizers to ensure that cement can flow around all sides of the casing (e.g., API RP 10D-2);
- Ensuring that the cement is (1) of adequate volume to cover protected water, oil, or gas bearing formations, flow zones, and corrosive zones with adequate excess; (2) designed for the in-situ conditions of the well; (3) designed for a minimum transition time as it sets; and (4) given enough time to reach adequate strength (API RP 65-2; forthcoming API RP 100-1); and
- Monitoring pressures during hydraulic fracturing stimulation and immediately ceasing stimulation if there is evidence of a loss of well integrity or formation integrity (API RP 100-1).

Well integrity issues have been reported in conventional and unconventional oil and natural gas wells at various phases (e.g., well construction, production, and post-production) and in various geographic settings (Davies et al. 2014; Jackson et al. 2014; King and King 2013). The rate of wellbore integrity problems increases with the age of the well (Brufatto et al. 2003) and also varies based on “the type of well, geographical location, maintenance culture of the operator,” and regulatory factors (King and King 2013).

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Topic:	**Wellbore integrity**
Question:	**Is guidance for ensuring lifetime integrity of OGD wellbores broadly and effectively implemented? Is available guidance sufficient to ensure lifetime integrity of OGD wellbores?**

(continued from previous page) Wellbore integrity depends, in part, on the type and design of cement used for its construction. The cement chosen depends on subsurface conditions (e.g., characteristics of the rock strata, temperature, expected pressures, and composition of the fluids encountered at depth). Cement suppliers must be sure that the formula they deliver accords with the well design. If gas flows into the cement while it is hydrating, or setting up, it may create channels or flow paths that negatively affect wellbore integrity (Soeder et al. 2014). Integrity issues may also arise because the steel casing and cement are subjected to deleterious chemical and physical conditions over time.

When drilling or fracturing a new well, fluids from the new well can accidentally connect with orphaned or abandoned wells, an event called communication between wells, which could potentially lead to changes in air quality or water quality. The number of orphaned and abandoned wells throughout Appalachia is estimated to be in the hundreds of thousands (records of oil and natural gas well operations were not generally kept before the 1950s) and the condition and location of many of these wells is unknown (Kang et al. 2015). Interactions between new wells and existing wells can be mitigated by conducting an “Area of Review” analysis to determine risks for contamination of protected groundwater through nearby conduits, including orphaned and abandoned wells, producing wells, plugged wells, and natural faults and fractures. Additional analysis to show that an adequate “confining layer” exists to ensure that there is a sufficient interval between the fractured zone and any protected water may be appropriate for wells with fractured zones in close proximity to protected water.

Research Goal and Examples of Research Activities: Wellbore integrity has and continues to be the subject of a considerable amount of research and many practice guidelines (e.g., API Guidance Document HF-1, 2009). The goal of research would be to determine whether guidance is being broadly and effectively implemented and is sufficient to ensure the lifetime integrity of wellbores as OGD technology and practices evolve. As noted above, many questions related to wellbore integrity are already under investigation and this work should continue. Some examples include:

- How can cementing techniques and materials be improved to ensure better bonding (e.g., self-healing cementing material that is also cost-effective) in different geologic media, including regions of high formation-fluid flow?
- Do abandoned and orphaned wells transmit fluids to groundwater or surface water as a result of communication with OGD wells? Do any mechanisms exist by which current activity a mile or more below the surface can affect the integrity of older conventional wells located closer to the surface?
- What is the number and condition of legacy and orphaned and abandoned wells in the region, what pollution problems are they causing now, and how can they be categorized by risk to help prioritize their remediation?
- Do current plugging techniques fully seal off flow zones and aquifers to demonstrably protect against contaminant transport and methane leakage?
- Under what circumstances are barriers other than cement appropriate to isolate critical zones within the wellbore?
- What impact might hydraulic fracturing have on cement integrity?
- How might acid mine drainage water impact wellbore integrity?
- What metrics would be appropriate to track, on a basin or state level, rates of well leaks to show changes in overall rates over time under different policy and technology environments?

Topic:	**Wellbore diagnostics**
Question:	**What tools and techniques can be developed to better assess wellbore integrity? How does wellbore integrity change over time?**

Background: A number of tools and techniques are available to assess wellbore integrity, although each has its limitations:

- Temperature log — used to verify the location of the cement. Temperature logs cannot be used to verify the integrity of the cement bond and are therefore not, by themselves, sufficient to assess wellbore integrity.
- Noise log — used to detect fluid flow behind casing by measuring the sound made by fluid as it flows.
- Cement evaluation log — any of a class of tools used to verify the integrity of annular cement bonding. Cement evaluation logs include, but are not limited to, ultrasonic imaging logs, variable density logs, cement bond logs, cement bond logs with a directional receiver array, ultrasonic pulse echo logs, and isolation scanners (Bureau of Land Management 2015).
- Cement bond logs without a borehole rugosity survey (e.g., a multi-arm caliper survey to determine the shape of the borehole wall) — uses an acoustic source and sensors to assess the quality of bond between the casing, the cement, and the formation. Results can be difficult to interpret for accuracy of a complete bond between casing and borehole wall.
- Borehole mapping tools that provide 360-degree maps of isolation — the most-effective methods to date for assessing wellbore integrity.
- Pressure testing — casing pressure tests for each string, formation integrity testing or leak-off testing prior to drill-out, and mechanical integrity testing prior to stimulation can all provide an assessment of well integrity. Unexpected deviations can be a sign of loss of well integrity (API RP 90-2). Most wells are equipped with annular pressure measuring technology.

Research Goal and Examples of Research Activities: As noted above, wellbore integrity has and continues to be the subject of a considerable amount of research and many practice guidelines (e.g., API Guidance Document HF-1, 2009; forthcoming API RP 100-1, 2015). The goal of research should be to identify and develop more reliable and accurate tools and techniques for analyzing wellbore integrity from design through well closure. Integrity needs to be monitored throughout the lifetime of the well, and in situ measurement devices could be developed to fill this need. Research could include studies to improve cased-hole imaging and automated analysis tools. The cement bond log and other related tools measure acoustic coupling. Research to develop a tool that directly measures cement placement is warranted.

3.3 AIR QUALITY

Emissions from OGD can affect the quality of air available to oil and natural gas workers, people living and working in surrounding areas, and ecological receptors and systems.

Topic:	**Emissions and air quality**
Question:	**What are the effects of OGD on air pollutant concentrations?**

Background: Emissions from OGD can create air quality problems that might affect oil and natural gas workers, people living and working in areas with OGD activity, and ecological receptors and systems (Appendix C). OGD operations emit a complex suite of air pollutants, including air toxics (e.g., benzene, toluene, ethylbenzene, xylenes, hydrogen sulfide, and formaldehyde),[1] criteria air pollutants (e.g., NO_2, $PM_{2.5}$), and silica. Atmospheric concentrations of these pollutants depend on emission rates, dispersion patterns and atmospheric transformations, all of which can be highly variable based on site-specific conditions. This variability complicates exposure assessments (e.g., non-occupational exposures that arise near OGD operations), especially exposures from intermittent sources or specific meteorological conditions. Concentrations that persist for a relatively brief period of hours to weeks (i.e., short-term) or for months to years (long-term) can both be problematic, depending on the toxicity and concentration of the pollutant and the extent of human exposure. The highest concentrations generally occur on or immediately downwind of an OGD facility or a cluster of facilities, but the spatial extent of the impacts is not well understood. Workers and nearby residents are not expected to experience the same exposures. For example, workers might be exposed to higher concentrations of chemicals in hydraulic fracturing fluids that are mixed at well pads or to chemicals in liquid and solid wastes that are handled at well pads. Quantifying the impacts of OGD activities on air quality requires knowledge of baseline pollutant concentrations from other sources that exist in the absence OGD operations.

Research Goal and Examples of Research Activities: The goal of research would be to quantify the contribution of emissions from OGD to atmospheric concentrations of a wide range of air pollutants — air toxics, criteria air pollutants, and other pollutants. This would likely require integration of measurements and modeling. New emission rate data would be needed to support exposure modeling, which must be validated with high spatial and temporal resolution measurements that quantify both short- and long-term concentrations during the entire life cycle of a well (i.e., development and production) and across the production system (e.g., well pads, gathering facilities, compressor stations, and processing plants). These measurements should be collected on and around a sufficient number of sites to capture the effects of the complex topography and differences in technology and operator practices on concentrations. The measurements and modeling should capture the spatial pattern of the pollutant concentrations around an OGD facility or cluster of facilities, not just peak concentrations that might occur at the fence line or on the site. The research should be designed to differentiate emissions from OGD activities quantitatively from those of other sources. The research would seek (1) to identify the specific OGD sources and processes that have the greatest air quality impacts, (2) to quantify the upper-bound potential for air quality impacts, (3) to compare the impacts of activities related to OGD with those from unrelated activities (e.g., motor vehicles, other industrial activities, and waste or biomass burning), (4) to evaluate and further develop models to predict air concentrations at OGD worksites and surrounding areas, and (5) to identify indicator pollutant species that could be used as markers for emissions from OGD operations.

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[1] Air toxics, also known as toxic or hazardous air pollutants, are pollutants known or suspected to cause cancer or other serious health or environmental effects (EPA air toxics website: *http://www.epa.gov/ttn/atw/*).

Topic:	**Criteria air pollutants**
Question:	**To what extent does OGD affect concentrations of ozone and $PM_{2.5}$?**

Background: Ozone and $PM_{2.5}$ are classified under the Clean Air Act as criteria air pollutants; therefore the EPA must set national ambient air quality standards for them. Concentrations of one or both of these pollutants exceed the standards in certain “non-attainment” areas both within (e.g., Pittsburgh) and downwind (e.g., Philadelphia, New York City, and Washington, D.C.) of the Appalachian Basin. If the standards become more stringent in the future, additional areas might also be designated as non-attainment areas.

Ozone is formed in the atmosphere from reactions of NO_x and VOCs in the presence of sunlight. Oil and natural gas operations also directly emit $PM_{2.5}$ and precursor gases (NO_x and some VOCs) that can react to form PM in the atmosphere. As noted in Appendix C, OGD can be a major source of NO_x and VOCs.

Research Goal and Examples of Research Activities: The goal of research would be to quantify the contribution of emissions from OGD to ozone and $PM_{2.5}$ concentrations in the Appalachian region and surrounding areas. The research would likely require a combination of measurement and modeling. Although extensive air monitoring networks exist in the Appalachian region, these networks are concentrated in urban areas rather than in the rural areas where many OGD operations are located. Data are needed to quantify baseline conditions and changes in concentrations of both precursor gases and ozone in and downwind of the Appalachian region. Emissions inventories would need to be compiled for $PM_{2.5}$, individual VOCs, and NO_x for both existing and potential future OGD facilities. The creation of these inventories would likely require the collection of new emission-rate data and activity data for the many processes used in the industry. These inventories must account for disproportionate contribution of high emitting sources (see below on high emitters). Existing and potential future development scenarios should consider the potential effects of changes in point-of-use emissions in, for example, the power sector, because of increased use of natural gas. Finally, chemical transport model simulations would likely be needed to quantify the contributions of OGD emissions to regional ozone and $PM_{2.5}$ concentrations. These models account for the nonlinear chemistry between OGD emissions and those from other sources.

Topic:	**High-emitters**
Question:	**What is the effect of high-emitters on air quality? How can high-emitter emissions be identified and resolved?**

Background: The magnitude of emissions varies widely across OGD facilities. The emissions are also highly skewed, with a relatively small number of facilities contributing disproportionally to the aggregate OGD-related emissions (Mitchell et al. 2015; Subramanian et al. 2015). The largest air quality impacts might occur in close proximity to high-emitters (Zielinska et al. 2010). Facilities with high emissions (high-emitters) must be represented accurately in emissions inventories (Zimmerle et al. 2015).

Large facilities (e.g. processing plants or large compressor stations) generally have higher emissions than smaller facilities (e.g. well pad with a single well) (Mitchell et al. 2015). However, smaller facilities can also be high-emitters. Like many other anthropogenic sources of air pollution (e.g., on-road vehicles) equipment malfunctions, accidents, operator error, or some other unintended failure of a process to operate in a normal or usual manner can cause even a small OGD facility to be a high-emitter. Intentional operations, such as blowdowns or venting, can also cause a facility to be a high-emitter. Although almost any facility has the potential to become a high-emitter, not every malfunction, accident, or error causes a source to have abnormally high emissions. The magnitude of emissions varies with operating and maintenance activities, which can cause high-emitters to be spatially and temporally dynamic. High-emitters are thought to be relatively few in number (Subramanian et al. 2015).

Research Goal and Examples of Research Activities: The goal of research would be to identify and quantify the prevalence of high-emitters, quantify the magnitude of their emissions, identify their causes, evaluate their impact on air quality (see above on emissions and air quality), and assess their contributions to overall emissions from OGD (see above on criteria pollutants and below on climate forcer emissions). The research would require rapid (potentially semi-quantitative) screening of emissions from a large number of widely distributed sources. For sites with unusually high emissions (e.g. emissions in the top few percent of facilities), targeted measurements would quantify the actual emission rates, their causes, and on- and offsite pollutant concentrations. Validated dispersion models could then be used to predict potential near-site air pollution concentrations for a wide range of site configurations to identify potential maximum concentrations. Research would likely be needed to develop techniques to identify and rectify high-emitters rapidly.

Topic:	**Climate-forcer emissions**
Question:	**What are the OGD emissions of methane and other climate-forcing pollutants?**

Background: A number of pollutants emitted by OGD, such as methane and black carbon, are climate forcers (gases or particles that alter the earth's energy balance by absorbing or reflecting solar radiation). OGD might benefit the climate because electricity generated with natural gas instead of coal emits less carbon dioxide. However, any climate benefits associated with this reduction in carbon dioxide emissions could be offset if there are emissions of climate forcers during the production and distribution of natural gas.

Research Goal and Examples of Research Activities: The goal of this research would be to quantify the emissions of climate forcers from OGD in the Appalachian region. The research would likely require measurements of emissions from individual sources and collection of activity data. Emissions rate and activity data would then need to be combined to create an inventory of climate-forcer emissions estimates for the region. The inventory should be tested against top-down, regional-scale field measurements. Major national research programs are already under way to assess methane emissions from the natural gas system as a whole (Environmental Defense Fund 2015b). Related research has also been conducted in the Appalachian region (Caulton et al. 2014; Goetz et al. 2015; Mitchell et al. 2015; Peischl et al. 2015; Subramanian et al. 2015; Swarthout et al. 2015). Research is also under way that might reduce emissions over time, such as the development of more efficient methods to identify natural gas leaks from various oil and natural gas equipment (e.g., Advanced Research Projects Agency – Energy 2014; Environmental Defense Fund 2015a; Houston Advanced Research Center 2015; Roscioli et al. 2015).

Topic:	**Air quality control**
Question:	**How effective are current and emerging OGD air-emission control and prevention technologies and practices?**

Background: Many approaches have been implemented or proposed to reduce the air emissions from OGD operations. Some are technologic controls, such as reduced emission completion (capturing natural gas and condensate that come up with hydraulic fracturing flowback to prevent their release into the air), vapor recovery units, oxidation catalysts, particle filters, and flares. Others involve operational practices, such as establishment of setback distances, use of natural gas instead of diesel fuel to power equipment, use of pipeline networks instead of trucks to transport water, and detection and repair of leaks.

Research Goal and Examples of Research Activities: The goal of research would be to quantify the effectiveness of various approaches for reducing emissions and pollutant concentrations in air. The research would involve field measurements of emissions and pollutant concentrations for facilities using a variety of control practices. Comparison of data pertaining to various phases of OGD and to various regions might be useful in evaluating the effectiveness of the technologies and practices. Techno-economic analysis could be performed to evaluate the advantages and disadvantages of various strategies; this would combine process modeling and engineering design with economic evaluation to understand the effects of innovation on the financial viability of emission-control technologies.

Topic:	**Indoor air radon**
Question:	**Does OGD increase indoor air concentrations of radon?**

Background: Natural radioactivity in shale rock produces radon-222 and its decay products, which can be present in natural gas produced from the Appalachian Basin. Subsequent use of natural gas in homes and commercial buildings can therefore lead to increased indoor radon concentrations. Radon-222 has a half-life of 3.8 days; its concentration declines as it travels from the well through pipelines to the point of use. The greatest risks are therefore likely associated with the use of vent-free heaters and cookstoves in locations close to production sites.

Research Goal and Examples of Research Activities: The goal of research would be to quantify the indoor radon concentrations associated with the use of natural gas from the Marcellus Shale and other resources in the Appalachian Basin. The research would require measurements of radon concentrations in natural gas at various well sites and points of end use. The research would likely need to account for the variability in natural gas residence times in transmission and distribution systems.

3.4 WATER QUALITY AND USE

There are widespread concerns about water contamination resulting from OGD activities, as well as water use and transport.

Topic:	**Water quality**
Question:	**What are the surface water and groundwater quality conditions before, during, and after OGD?**

Background: Reports of surface water and groundwater contamination allegedly caused by OGD have garnered significant public attention. However, in some of these cases the contamination might have been caused by other sources, and in many cases the baseline quality of the water had not been determined before the development began. For example, some private drinking water wells in areas experiencing OGD contain naturally occurring methane (Baldassare et al. 2014; Bowman et al. 2014a; Bowman et al. 2014b). Knowledge of baseline conditions is essential to any scientific assessment of impacts, but baseline water quality conditions have rarely been assessed in the Appalachian region. Baseline conditions cannot be determined from currently available data for the range of potential OGD-related stressors. They do not provide sufficient spatial and temporal resolution or the necessary analytic chemistry detail to distinguish among the influences of various anthropogenic sources (e.g., roadway runoff or point-source discharges) and natural sources (e.g., variation in the underlying geologic formations). Development and implementation of a monitoring strategy designed to make these distinctions are therefore needed.

Research Goal and Examples of Research Activities: The goal of research would be to quantify the impact of OGD on short- and long-term trends in the quality of water resources. Specific objectives would be (1) to design the optimal framework for determining baseline conditions and assessing impacts on water resources with the broadest possible geographic applicability, (2) to implement the framework at a variety of sites that represent the variability encountered across the Appalachian region, and (3) to analyze and interpret the resulting data to identify short- and long-term trends in the quality condition of water resources. The framework should be designed to ensure robust studies by specifying the spatial and temporal aspects of sampling needed to distinguish among conditions before, during, and after development; the types of samples that should be collected; the analytes and reporting limits that should be included; and the quality assurance protocols necessary to achieve the desired levels of precision and accuracy. Protocols for implementing the framework at individual sites should include data quality objectives and a data analysis plan that results in a statistically valid, scientifically defensible assessment of the short- and long-term trends in the quality of the water resources. A well-considered framework would maximize the likelihood of obtaining useful and timely answers to questions about the potential impacts of OGD on surface water and groundwater quality. Such data would also provide the basis for assessing exposures of ecosystems and humans to affected water.

Topic:	**Water use**
Question:	**What water-use requirements are needed to protect ecosystems affected by OGD? How does local hydrology effect water use? How will new reuse or recycling technologies affect future water demand?**

Background: Excess water withdrawals for hydraulic fracturing, particularly in arid or low-flow regions, could impact river and stream flows (Brittingham et al. 2014). Stream flows that drop below critical levels can directly impact ecosystem services (i.e., the benefits human beings get from ecosystems). An example of an ecosystem service is a recreational fishery — certain sport fish need a minimum flow of water to get enough oxygen, or be in an optimal temperature range. Information about low-flow requirements would help people who manage water withdrawals to protect ecosystem services as well as the basic functioning of the ecosystem, including headwaters, cold-water trout fisheries, and wetlands.

Research Goal and Examples of Research Activities: The goal of research would be to quantify low-flow requirements specific to the region's surface-water bodies to support a range of purposes while accounting for seasonal and year-to-year variability in flow rates. To assess impacts of water withdrawals on local-stream flows, hydrological models need to be developed for individual basins. For example, in the Appalachian region, surface mining activities and flooded mine pools present challenges in understanding surface and subsurface hydrology. It would also be important to assess how future water demand will be affected as more hydraulic fracturing water is recycled and re-used and as modified drilling practices come into play. This information would support evaluations of how water use for hydraulic fracturing, agriculture, and other applications collectively affect stream flow.

Topic:	**Water quality diagnostics**
Question:	**What are the sources of water contamination potentially related to OGD, and how can they be identified or distinguished?**

Background: Although concerns have been expressed about water resources becoming contaminated by drilling, hydraulic fracturing, intentional releases (such as brine application on roadways), and accidental releases (such as surface spills of stored wastewater), limited research has been conducted to define the impacts of oil and natural gas development on surface water and groundwater quality. In assessing the potential for hydraulic fracturing to affect the quality or quantity of drinking water resources and identifying factors that affect the frequency or severity of any such effects, the EPA (2015) reported that it

> … did not find evidence that [hydraulic fracturing] mechanisms have led to widespread, systemic impacts on drinking water resources in the United States[1]. Of the potential mechanisms identified in this report, we found specific instances where one or more mechanisms led to impacts on drinking water resources, including contamination of drinking water wells. The number of identified cases, however, was small compared to the number of hydraulically fractured wells.

Research to date has focused on the potential contamination of drinking water aquifers with methane, but the source(s) of the methane (and other OGD-related stressors in water) and the best methods of determining them have been debated. For example, the source of methane in freshwater aquifers could be biogenic, formed near the ground surface by biologic activity, or thermogenic, formed in deep shale or shallower coal beds from high temperature and pressure conditions acting on organic material. Further, methane could migrate along various pathways, including from coalbeds, an old well that was improperly abandoned, a new well with compromised wellbore integrity, or along natural faults and fractures.

As noted earlier, assessing baseline conditions is critical — although this knowledge is not sufficient. Determining the sources of methane in an aquifer can be quite challenging, and studies of methane in groundwater have been controversial (Darrah et al. 2014; Jackson et al. 2013; Llewellyn et al. 2015; Sharma et al. 2014a; Siegel et al. 2015; Vidic et al. 2013). In addition, the question of source depends on the specific well boring, site geochemistry, and geologic stratum, with the result that conclusions from one study might not apply to the next.

Research Goal and Examples of Research Activities: The goal of the research would be to establish better forensic methods (e.g., geochemical and isotopic fingerprinting) to identify the sources of methane, brine, and other contaminants in groundwater. Collection of concentration data from freshwater aquifers that represent background conditions (i.e., the conditions that exist in the absence of OGD and that might be attributable to other anthropogenic sources and natural sources) would be a significant help in determining whether new oil and natural gas wells are the sources of contaminants.

Some researchers are already investigating methods of tracing sources that involve isotopic composition. A study by Chapman et al. (2012) suggests that strontium isotope ratios could be used to diagnose episodes of groundwater and surface water contamination related to Marcellus brines (see also Capo et al. 2014 and Vengosh et al. 2013).

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[1] With this conclusion, EPA recognized a number of significant limiting factors, including: “insufficient pre- and post-fracturing data on the quality of drinking water resources; the paucity of long-term systematic studies; the presence of other sources of contamination precluding a definitive link between hydraulic fracturing activities and an impact; and the inaccessibility of some information on hydraulic fracturing activities and potential impacts.” (EPA 2015)

Topic:	**Water quality diagnostics**
Question:	**What are the sources of water contamination potentially related to OGD, and how can they be identified or distinguished?**

(continued from previous page) However, an adequate isotopic catalogue for brines from the various strata is not available at present. Studies have indicated that migration of methane could potentially affect its molecular and isotopic fingerprint, creating complications for source identification (Sharma et al. 2014b). Additional tools would be useful to identify methane, other volatile contaminants, and radioactive materials detected in drinking water that might have originated from a wellbore or a deep geologic formation. For example, it would be useful to identify tracers that can be used to distinguish contamination resulting specifically from hydraulic fracturing. These and other types of tools and techniques would be invaluable to detect sources of any of a wide range of contaminants, whether or not they originate from OGD, for the purpose of refining protocols to help prevent future contamination.

Topic:	**Water transport**
Question:	**What are the advantages and disadvantages of the various means of supplying water to and transporting wastewater from OGD well pads for off-site management?**

Background: Some of the millions of gallons of water per well that are used for hydraulic fracturing are brought to the well pad by tanker truck, requiring dozens of truck deliveries per day for a period of many weeks to months at a time. Water is sometimes piped to well pads and some well pads use groundwater wells. A newer trend is to reuse flowback or produced water to augment water needed for hydraulic fracturing and other processes (Rodriguez and Soeder 2015; Veil 2015). Wastewater is often transported by truck or pipeline for off-site management, which could include some form of disposal or use in other operations. The choice of how to supply water to and transport wastewater from well pads is a traditional cost–benefit decision made by management, although there are in fact other considerations and externalities apart from cost.

Research Goal and Examples of Research Activities: The goal of research would be to develop an analytic framework that includes the externalities (see Yang et al. 2015), such as infrastructure costs and their maintenance (e.g., roads or bridges), loss or gain of ecosystem services, effects on competing users, habitat fragmentation, erosion issues, and issues of human well-being (e.g., accidents or injuries).

3.5 WASTE MANAGEMENT

Appropriate management of solid and liquid waste from OGD is crucial to prevent potentially harmful exposures.

Topic:	**Accidental waste release**
Question:	**What are the frequency and characteristics of accidental releases of OGD solid and liquid waste? How can collection and sharing of data documenting these releases be improved? How can the regional extent of the plume of pollutant released be identified?**

Background: OGD wastes can be released to the environment as a result of spills, leaks, blowouts, and other unintentional events. Such discharges to the environment can occur as a result of accidental spills during mixing, injection, and return of spent hydraulic fracturing fluid; flooding of impoundments; and failure of liners or containers for stored waste fluids (Brantley et al. 2014; Kell 2011; Rahm et al. 2015). Solid wastes (e.g., drill cuttings and tank sludge) are sometimes stored onsite before they are transported to landfills for final disposal or for treatment and reuse in other processes (e.g., abandoned mine fill; Phan et al. 2015). Accidental releases are possible during the storage, transport, or disposal of wastes.

Methods for reporting and documenting accidental spills depend on the applicable regulations overseeing the well pad operations, the procedures followed by the operators of the drill site and their subcontractors, and the rules governing the waste hauler. The documentation of waste disposition and the documentation's availability to other agencies and the public are not always clear and depend on regulatory requirements and policies and on other parties that oversee spill incidents.

Research Goal and Examples of Research Activities: The goal of this research would be to define and document accidental releases of wastes in a manner that could facilitate the study of impacts from the releases and how they might be avoided or mitigated. Common rules, regulations, and reporting requirements that are the responsibility of personnel involved with wastewater management, handling, treatment, disposal, and regulatory oversight are already in place (e.g., Clean Water Act and Safe Drinking Water Act). Reports prepared in accordance with these requirements could be documented and archived in electronic format to create a useful database. A comprehensive database would facilitate research on the frequency and severity of the types of OGD spills; for practical reasons, such a database would be developed starting with existing systems for reporting data and information related to OGD (e.g., FracFocus and state-specific versions of the Groundwater Protection Council's Risk Based Data Management System). A rigorous multivariate analysis of the data about events involving accidental or unauthorized releases might detect patterns that could guide the continued evolution of practices to prevent, detect, contain, and remedy such releases. The database could also be useful for understanding and preventing public safety hazards related to accidental releases and explosions. As noted in Section 3.1.8, collaborations among multiple stakeholder groups would be critical to achieve a practical and effective database.

Topic:	**Permitted waste management**
Question:	**What are the potential impacts from permitted practices for managing OGD solid and liquid waste? What are the most-effective practices for managing wastes from OGD?**

Background: Solid and liquid wastes (flowback water, produced water, drill cuttings, and drilling fluids) are generated at various phases of OGD. These wastes have been managed by various means of treatment or disposal, primarily in accordance with state regulations. OGD is subject to some federal regulations but with some exceptions (e.g., exemption from hazardous waste regulations under Subtitle C of the Resource Conservation and Recovery Act). The most-effective practices are those that contain the waste, treat it for reuse, or, if these options are not viable, dispose of it in a secure manner, such is in a landfill or by means of deep-well injection in an underground injection control well. Underground injection control wells are used for placing wastewater deep underground. The disposal choice depends on the type and degree of contamination and whether the wastes can be economically and safely reused or recycled. Much of the liquid waste can receive simple treatment and be reused if there is a nearby well that needs to be hydraulically fractured. Liquid waste that is contaminated with potentially hazardous constituents (e.g., heavy metals or NORM) must be analyzed and a determination made to either treat and reuse the liquid or dispose of it by deep-well injection. Solid wastes, similarly, are recycled, reused, or disposed of in landfills that comply with state and local regulations and the Resource Conservation and Recovery Act. In some cases, permitted discharges of inadequately treated OGD wastewater have been linked to impacts on surface water quality (See Appendix C). Consideration of these potential impacts has and should continue to inform most-effective practices.

Wastewater might be reused for beneficial purposes such as dust suppression. Additionally, concentrated residual wastes created from various forms of wastewater treatment, such as for reuse or for permitted surface discharge from centralized wastewater treatment facilities, also necessitate consideration and research. Further, improved understanding of the quantity of wastes managed by various methods would inform research in this area.

Research Goal and Examples of Research Activities: The goal of research would be to establish a framework that uses reliable physical, chemical, and radiologic characterization methods to manage wastes safely. The framework should include careful data collection and preservation techniques; timely accurate, and sufficiently thorough laboratory analysis of physical, chemical, and radiologic characteristics of wastes; full-scale, field-tested analysis of the efficacy of treatment technologies and methods (moving beyond laboratory testing and pilots); implementation of appropriate quality assurance and quality control protocols; and consistent data analysis procedures in order to provide reliable data throughout the treatment, reuse, and disposal processes. Standard analytical methods are needed to more fully characterize some OGD-related wastes for use within this framework. The framework would be useful to address all types of waste (e.g., effluent from Central Wastewater Treatment facilities, radiation-containing solid waste sent to landfills, wastewater disposed of in underground injection wells).

As described above regarding accidental spills of OGD waste, such a framework ideally would be developed starting with existing systems for reporting data and information related to OGD (e.g., FracFocus, state-specific versions of the Groundwater Protection Council's Risk Based Data Management System and other state agency databases, and reviews by the State Review of Oil and Natural Gas Environmental Regulations). However, reliable data alone are not sufficient to assess potential impacts; data also need to be electronically archived in a consistent manner for ongoing environmental impact assessment. State regulations vary in the requirements for handling, treating, and discharging raw and treated wastes. Comparing the waste management methods used in various hydrocarbon plays with the various state requirements would be useful in determining the most protective waste handling and treatment systems.

3.6 INDUCED SEISMICITY

Earthquakes can be induced by activities relating to OGD. Appropriate most-effective practices are necessary to reduce the likelihood of induced seismicity.

Topic:	**Induced seismicity causes**
Question:	**What geologic conditions and engineering practices contribute to induced seismicity?**

Background: Earthquakes are caused by movement on faults. Stress naturally builds up on faults until it reaches a level at which movement is triggered, resulting in an earthquake (seismic event). Injection of fluid into the subsurface can cause changes in pressure that, under certain conditions, trigger movements that result in an earthquake. Earthquakes triggered by such human activity are known as induced seismic events.

Recently, small earthquakes and earthquake swarms (i.e., numerous earthquakes occurring over a relatively short period of time) associated with oil and natural gas waste injection have been identified in Ohio, Arkansas, and Oklahoma (McGarr et al. 2015; Weingarten et al. 2015). These small earthquakes have raised public concern about the potential for hydraulic fracturing, liquid waste disposal, and enhanced oil recovery (McGarr et al. 2015) to cause damaging earthquakes. To date, only a small number of felt earthquakes have been linked to hydraulic fracturing. The vast majority have been linked to the injection of oil and natural gas wastewater in deep formations.

Research Goal and Examples of Research Activities: The goal of research would be to build on work already under way by the U.S. Department of Energy, Bureau of Reclamation, the U.S. Geological Survey, several state geological surveys, and others to better understand the relationship between the characteristics of induced seismic events (e.g., rate and magnitude) and the geologic conditions (e.g., fault locations), injection well placements, and temperature, volume, and pressure of injection fluids associated with them.

Topic:	**Induced seismicity prevention**
Question:	**What predictive methods and preventive practices are most effective in mitigating induced seismicity caused by disposal of OGD wastewater in underground injection control wells?**

Background: Recent swarms of induced seismic events have been linked to oil and natural gas activities, particularly deep-well injection of liquid waste, as described in recent literature cited above in the discussion of induced seismicity causes (See Appendix C). Until the past few years, most underground injection wells were permitted without regard for their potential to generate earthquakes. Many injection wells may thus be operating with engineering practices that are not designed to minimize induced seismic activity.

Research Goal and Examples of Research Activities: The goal of this research would be to develop practices to mitigate the risk of induced seismic events associated with wastewater injection. Data from studies of seismicity causes (see above) could be used to develop criteria for predicting the risk of induced earthquakes before well permitting, construction, and operation begin. Mitigation could be added to the most-effective practices in the event that an existing well has been linked to induced seismicity. Initial studies could investigate the success of hazard mitigation using local “traffic light” systems, which reduce injection rates after episodes of linked seismic activity (McGarr et al. 2015).

3.7 CHEMICAL TOXICITY

The identity and toxicity of some chemicals and chemical mixtures in hydraulic fracturing fluid and wastewater from OGD are not known.

Topic:	**Chemical toxicity (human and ecological)**
Question:	**What are the composition and toxicity of chemical mixtures unique to OGD and how can their toxicities be determined? How does toxicity change over time due to microbe–water–rock interactions in reservoirs over the lifetime of the well?**

Background: The efficacy of hydraulic fracturing technologies depends in part on the use of fracturing fluid containing a variety of chemicals (e.g., EPA 2015 and Stringfellow et al. 2014). Information for a number of ingredients indicates that they are of low toxicity (e.g., Gradient 2013 and Stringfellow et al. 2014). However, many ingredients have inadequate toxicity information (EPA 2015), and others are considered confidential business information with potential for toxicity unknown by the public. As such, the chemical by-products that may result from mixing hydraulic fracturing fluids are currently unknown.

During well completion, some of the injected fracturing fluid comes back out of the well along with water native to the local geologic formation (known as formation water). This mixture of fluid is called flowback water. In the production phase, the fluid that comes back out of the well over time has a larger proportion of formation water than that found in flowback water; this fluid is called produced water. Produced water can contain high concentrations of a number of potential chemical health stressors (e.g., heavy metals, NORM, and some components of brine), and potentially transformation products resulting from reactions that occur at depth, under naturally high temperatures and pressures. Efforts continue to characterize flowback water (e.g., Ziemkiewicz and He 2015) and produced water from wells in Appalachia and other regions (Rowan et al. 2015 and Sharma et al. 2014b). The composition of flowback water and produced water can vary depending on geologic conditions as well as the variable composition of the hydraulic fracturing fluid. Assessments of risk to human and ecological health would benefit from more information about the toxicity of chemicals and chemical mixtures in fracturing fluid and related wastewater that is relevant to the exposure levels that might be experienced by (1) workers while mixing or otherwise managing these liquids, and (2) nearby community members in instances where the management of wastewater does not prevent exposure.

Research Goal and Examples of Research Activities: The initial goal of research would be to improve the understanding of the composition, including its variability, of hydraulic fracturing fluid, flowback water, produced water, and other wastewater, as well as the concentrations of wastewater components in environmental media to which people might be exposed. Research should then attempt to understand how the chemical composition of produced water changes over the lifetime of the well as the fluids interact with rocks and microbes in the producing reservoir. This information, combined with an understanding of the type and magnitude of potential exposures, is important for deciding if toxicological studies are needed. The goal of subsequent research would be to conduct toxicological evaluations where they would be helpful in decision-making about the protection of human and ecological health. Toxicity testing would not be useful in deciding whether direct contact with produced water is safe because it is already well-known that such exposure should be avoided. However, a better understanding of the potential toxicity of hydraulic fracturing fluid and related wastewater could be useful in other contexts, for example, to help local public health and other authorities if they need to respond to accidental releases to the environment or implement risk-based decisions about management of the wastewater.

3.8 ECOLOGICAL HEALTH

OGD has been shown to change the ecosystems in which it occurs. Understanding these changes and their impacts is important. Separate questions have been formulated to address chemical stressors and landscape change because the latter is inevitable to varying degrees over the life cycle of OGD and the former is potentially preventable.

Topic:	**Ecological health effects (landscape change)**
Question:	**Do the short- and long-term landscape changes associated with OGD affect terrestrial and aquatic habitats and present risks to ecological health?**

Background: The Appalachian Basin region is a biologically diverse source habitat for many species associated with large blocks of contiguous forests. OGD results in physical and sensory changes to the landscapes in which it occurs (Allred et al. 2015).

These changes can be dramatic. Roads, pipelines, and well pads open and fragment existing habitat. They change vegetative cover and microclimates and create hardscapes and other artificial land cover. They reduce core forest habitat. Water withdrawals can change depth, temperature, and other physical attributes of aquatic habitats. All of these changes have known ecological effects (Appendix C).

In addition to physical changes to the environment, sensory changes can also occur (see Appendix C). Noise and light are generated around the clock during well development. Compressor stations can emit significant noise continuously throughout the lengthy production period. Elevated noise and light are known to interfere with natural population and community dynamics, including communication, mating, and prey or predator location. Little is known about how these stressors interact or about their cumulative effects.

Research Goal and Examples of Research Activities: The goal of this research would be to quantify the contributions of OGD in the Appalachian region to changes in physical habitats and sensory stressors and to assess the ecological risks that result from these changes. Changes of interest include losses or changes in vegetation cover, exposure to noise and light pollution, invasion by non-native species, increased erosion and sedimentation, and changes in microhabitat and hydrologic dynamics. The research would likely involve measuring and modeling these changes and analyzing them spatially. Abrahams et al. (2015) is an example of this kind of research.

Ecological risk assessment would likely require the selection of model or representative systems or species for which detailed measurements can be made in areas affected by OGD and in control areas free of such development. Although research addressing these risks might be informed by the literature, the specific risks posed by interactions of OGD-related sensory and physical stressors might be novel. Modeling and detecting cumulative risks would also be challenging.

Topic:	**Ecological health effects (chemical and radiation)**
Question:	**Are there chemical and radioactive ecological exposures that result from OGD and acute or chronic ecological health risks associated with these exposures?**

Background: Potential contamination of freshwater aquifers from OGD operations has been a primary focus of study given concern about drinking water quality. These aquifers might be accessed by terrestrial vegetation, especially during dry periods. They can also be important contributors to surface water. Thus contamination of shallow aquifers is a potential issue for both terrestrial and aquatic ecosystems. Aquatic and terrestrial ecosystems might also be affected by accidental spills or poor waste management. OGD also exposes ecological communities (and people) to a variety of air emissions that are themselves recommended areas of study (see Section 3.3 on air quality).

Non-lethal levels of potential environmental stressors (e.g., heavy metals, NORM, and some components of brine) brought to the surface by oil and natural gas extraction can make their way through soil or water into plants and organisms that are low on the food chain. Subsequently they can bioaccumulate to levels of concern in organisms that are higher on the food chain.

OGD-related chemicals that reach water, soil, or air might be a concern for pets and domestic livestock. These animals could in turn serve as bioindicators of risks to people or wildlife.

Research Goal and Examples of Research Activities: The goal of research would be to quantify the chemical exposures, singly and in combination, of wild flora and fauna, pets, and domestic livestock to contaminants from water, soil, and air pollution associated with OGD. In addition, research is needed on ecological risks associated with these exposures. Little is known about the interactions of the OGD-related stressors with other natural and anthropogenic sources of stressors or the resultant ecological exposures or risks. Both monitoring and modeling will be needed.

Impact research should focus on populations and species for which evidence of vulnerability (caused, for example, by habitat location or functional role in affected ecosystems) has been reported. Examples include domestic livestock and flora and fauna that live at the interface of terrestrial and aquatic systems.

Topic:	**Ecological health effects (cumulative)**
Question:	**Are there important additional risks that result from cumulative exposure to multiple ecological health stressors (e.g., physical, sensory, radioactive, or chemical) associated with OGD?**

Background: The EPA (1999) has noted that the combined, incremental effects of human activity can accumulate over time and result in the degradation of important ecological resources. This observation may also hold true for OGD. Cumulative effects may occur among physical, sensory, chemical, or radioactive stressors.

Research Goal and Examples of Research Activities: The goal of research would be to monitor and model the cumulative and interacting effects of physical, sensory, chemical, and radioactive changes in the environment caused by OGD. For core forests, for example, a key component of the research would be to determine the threshold levels of core forest beneath which fragmented populations would experience increased vulnerability to various stressors (e.g., noise and light as well as air, water, and soil pollution). Alternatively, the research would also include the assessment of changes in population and community functions in response to noise or light pollution — such as disrupted gene flow or changes in reproductive or foraging behavior associated with noise pollution — that might be exacerbated by chemical stressors or physical changes in habitat quality or quantity. Known effects of invasive species might be altered when they occur in highly fragmented landscapes or in the presence of air, water, or soil pollution.

Topic:	**Ecological health effects (mitigation)**
Question:	**What practices are most effective for mitigating OGD-related physical and chemical stressors that might contribute to ecological impacts? Do these practices protect the most vulnerable ecological elements?**

Background: Because OGD differs from previous oil and natural gas development activity, new standards for most-effective practices might be needed. Both industry and public agencies have developed guidance documents for minimizing impacts (e.g., The Nature Conservancy 2015), but few studies have examined the effectiveness of these guidelines. However, the Pennsylvania Department of Conservation and Natural Resources has released a report summarizing the first year of OGD monitoring data collected at state forest lands where the state's guidance document was followed (http://www.dcnr.state.pa.us/cs/groups/public/documents/document/dcnr_20029147.pdf).

Most-effective practices need to be identified for restoration of land used for OGD well pads, roads, and pipelines. Identifying such practices depends on a clear and broad understanding of how OGD might affect ecosystems. For example, some site-approval processes focus on conditions at the proposed well pad but do not take into account cumulative landscape impacts.

OGD might have direct effects on the populations and demographics of species of high conservation concern and on habitats and ecosystems that are rare or of particular ecological or environmental importance. Although each state in the Appalachian region has programs to protect endangered species, the impact of OGD on population distribution, demography, and genetic exchange for such species is unknown. In addition to these species, habitats and very specific geographic areas have been designated by states and environmental organizations as being of high conservation concern. Some species might suffer losses through direct mortality on OGD well pads or roads. Others might face increased risk from disruptions in gene flow and in other population and community functions as a result of landscape changes. Such increased risks would be of particular concern for species that are already threatened or endangered.

Research Goal and Examples of Research Activities: The goal of research would be to assess the effectiveness of mitigation strategies in addressing the exposures, risks, and impacts described in questions raised above. These mitigation strategies range from state-approved processes and regulations to industry self-regulatory agreements and landowner procedures and requirements. Important comparative opportunities exist among the various strategies used by states and other authorities. Two examples of the kinds of studies that would address this research question would be (1) assessment of the frequency and pattern of off-specification events and other accidental conditions occurring under various mitigation strategies and (2) a comparison of outcomes for states that allow surface disposal of produced water with those for states that do not.

Another example of research on most-effective practices would be mapping likely oil and natural gas development over the ranges of all threatened and endangered species in the Appalachian region. This would allow examination of the natural history and habitat requirements of the affected species and provide guidance to conservationists about how best to protect them. The research should also study hotspots of future development activity (Johnson et al. 2010), assuming that development of the entirety of the Marcellus and Utica plays is unlikely to occur. Modeling and monitoring schemes to predict and detect impacts on population distribution, demography, and genetic exchange for identified species would be useful tools for this type of research.

Standards for post-production site restoration are also needed. General knowledge of ecosystem restoration is relevant but "success will be best achieved by careful, and detailed examination of currently affected landscapes" (Drohan and Brittingham 2012). The risks of abandoned and orphan wells are significant (Kang et al. 2014), indicating the need to have a well-documented inventory, and to develop tools to ensure proper well plugging and sealing of OGD wells. Because the landscape changes associated with OGD are different in scale and pattern (e.g., lower density of well pads with larger area per site) from those associated with conventional well development (e.g., higher density of well pads with smaller area per site), new techniques of site restoration might be needed.

3.9 HUMAN HEALTH AND WELL-BEING

Questions have been raised about the potential for human health risks associated with OGD. A limited amount of research has endeavored to answer some of these questions but to date has not provided definitive answers.

3.9.1 Human Exposure and Health Risk Assessment

Understanding exposure pathways is the first step toward understanding potential risks to health for oil and natural gas workers and people living in communities near OGD. The degree of exposure for community members depends on many factors, such as emission controls and setback requirements. The degree of exposure for workers also depends on many factors, notably health and safety planning and training and recommendations for, and use of, personal protective equipment.

Topic:	**Total human exposure**
Question:	**How can total human exposures to OGD stressors be estimated? What exposure pathways and phases of OGD should be considered in estimating the exposure?**

Background: Oil and natural gas workers and people living in communities near OGD might be exposed to a variety of OGD-related health stressors. Examples include volatile chemical emissions to air while workers mix hydraulic fracturing fluid, fine particulate emissions from engines powered by diesel or natural gas, dermal contact with stressors in solid or liquid waste, or noise and vibration emanating from drill rig operations (Appendix C). Worker exposures might be prevented or minimized with the use of health and safety protocols.

Identifying potential OGD-related health stressors and quantifying the contributions of specific activities (e.g., diesel traffic, chemical and sand use, or wastewater management) to exposure to the stressors are key to understanding potential sources of health risks. Quantifying an individual’s total exposure through multiple exposure pathways is a vitally important component of health risk assessment and research. In recent epidemiologic studies of communities near OGD, exposure has been assessed using either simple surrogates (e.g., the number of wells in a study area or the distance between a well and a residence) or environmental concentration data (e.g., outdoor air quality data collected with area samplers) (Casey et al. 2015; Hill 2013 [not published in a peer-reviewed journal]; Jemielita et al. 2015; McKenzie et al. 2014; Stacy et al. 2015). Few studies have estimated exposures using more rigorous methods.

Research Goal and Examples of Research Activities: The goal of research would be to identify and quantify health stressors associated with OGD to which workers and community members might be exposed. Identifying potential chemical, physical, and sensory health stressors involves developing an inventory of their sources. From these sources, stressors might be released to air, soil, groundwater, or surface water bodies. Once released to the environment, people might be exposed to them. Of these exposures, those that have the potential to affect health should be quantified using more rigorous methods. These methods might include personal monitors or environmental concentration data for health stressors combined with data about (1) the oil- and gas-related sources (e.g., drill rigs, vehicle emissions, or wastewater discharges) of each health stressor, (2) the spatial and temporal variations in the concentrations or amounts of the health stressors, (3) the time–activity patterns of the exposed individuals, and (4) the contributions of sources of exposure that are unrelated to OGD. One effective exposure assessment method is biological monitoring (the subject of the following research question).

Topic:	**Human biomonitoring**
Question:	**Are there biomarkers of exposure that are useful for understanding total exposure to OGD-related health stressors? Are there biomarkers that reflect health risks (e.g., chronic inflammation, DNA damage, and oxidative stress) specific to OGD?**

Background: OGD might release various health stressors to environmental media (e.g., water and air), with the potential to reach a worker or community member through multiple routes of exposure (e.g., inhalation, ingestion, or dermal contact). The development of health effects depends on an individual's total exposure by way of all routes and media. The exposure of an individual or population can be assessed by estimating *external* exposure (e.g., mapping distances to sources, defining job exposure categories with respect to the degree of exposure, or measuring contaminant concentrations in environmental media) or estimating *internal* doses (i.e., concentrations of contaminants or their metabolites in biological matrices of exposed individuals). Commonly used biological matrices include blood, urine, hair, and breath. Estimating exposure by quantifying biomarkers in biological matrices is called biomonitoring.

Some have attempted to estimate exposures associated with OGD by way of biomonitoring (Esswein et al. 2014). The results of these studies, which were limited to worker exposures, were inconclusive because of a small sample size and methodological limitations that may not have accurately captured the critical time window of exposure.

Health effects can be difficult to assess clinically, especially for chronic effects that might not be significant enough in early stages to manifest as clinical symptoms or other outcomes. Some chronic effects might only be apparent clinically after the time window that a study can afford to address. Biological changes, or biomarkers, of early effects might be able to provide an intermediate indication of potential effects well before results become available from multi-decade epidemiologic studies of chronic effects such as cancer.

Biomarkers found at the tissue, cell, or molecular levels that reflect a range of pathophysiologic effects (e.g., inflammation, oxidative damage to DNA and cells, vascular dysfunction, or metabolic dysfunction) can be useful for predicting disease risks before the development of clinical symptoms. Some of these biomarkers have been used in studies of air pollution health effects and of tobacco-smoke health effects; they have also been used to aid in disease diagnosis and therapeutic drug development. To date, such biomarkers have not been used in health studies of the effects of OGD to understand how the biomarkers might change in response to OGD and, if they do, whether the changes correlate with changes in disease risk.

Research Goal and Examples of Research Activities: The goal of research would be to identify biomarkers of exposure and effect that are relevant to potential OGD exposures. Proteomics, metabolomics, and other emerging fields are promising tools to help look for cellular and subcellular responses to exposures to disease-causing agents. Useful biomarkers of exposure or effect would support assessments of risk that could begin to answer questions about potential (particularly long-term) health effects in advance of conducting lengthy prospective epidemiological studies.

3.9.2 Oil and Natural Gas Worker Health

Intensive and rapidly changing OGD work environments feature potential stressors that require renewed and ongoing safety and health research. The degree of worker exposure to these stressors can depend on the appropriate recommendations for and use of health and safety protocols.

Topic:	**Worker health effects (chemical and radiation)**
Question:	**Under what conditions and to what extent are OGD workers exposed to chemical or radioactive health stressors? Do these exposures lead to health effects?**

Background: The OGD work environment can feature a range of health stressors, individually or cumulatively. The degree of worker exposure to these stressors can depend on the appropriate recommendations for and implementation of safety protocols.

Some sources of acute toxicity associated with OGD, such as hydrogen sulfide gas, are well known (e.g., Gabbay et al. 2001 and Hendrickson et al. 2004). Others, such as the extensive use of silica, represent well-known, chronic exposures in new settings, requiring new and consistent approaches to control. Recently identified acute hazards (e.g., VOCs; Esswein et al. 2014) found by on-site sampling may not be fully understood. In addition, recent sudden death events (King et al. 2015) have raised questions about potential chronic neurotoxicity or cardiotoxicity. The presence of confined spaces and uncharacterized mixtures can increase the risk of exposures of potential concern.

It is important to consider the potential for acutely toxic exposure conditions and for chronic toxicity from lower-level exposures to chemical mixtures in hydraulic fracturing fluids, flowback and produced waters, stored hydrocarbon products, and fugitive emissions. The Committee has not identified medical surveillance reports or other morbidity and mortality statistics that are specific to OGD worksites.

Research Goal and Examples of Research Activities: The goal of research would be to characterize and, if necessary, identify techniques for mitigating, exposures to health stressors of potential acute and chronic toxicity (e.g., silica and VOCs). These stressors have been the subject of recent study (Esswein et al. 2013; Esswein et al. 2014) and should continue to be a primary research focus. To the extent feasible, exposure surveys and biomonitoring should be conducted to supplement current knowledge and documentation of exposure hazards on OGD worksites. Medical surveillance of workers would provide other opportunities to characterize health outcomes and to identify biomarkers of exposure or intermediate health outcomes. Enrollment of a worker population in prospective studies would support both the long-term health of workers and the long-term success of the industry. Research on OGD equipment and engineering processes designed to prevent worker injuries, fatalities, and chronic disease by anticipating them, rather than relying on measures that are dependent on human behavior (e.g., the use of respirators and other personal protective equipment), are particularly desirable.

Topic:	**Worker health effects (sensory and accidents)**
Question:	**Under what conditions and to what extent are OGD workers exposed to chronic sensory (e.g., noise and vibration) or acute physical hazards (e.g., vehicular accidents, falls, and burns)? What are the acute traumatic consequences? What are the chronic disease consequences, such as hearing loss?**

Background: Many OGD jobs are associated with potential exposures to substantial noise and in some cases vibration. The degree of worker exposure to these stressors can depend on the appropriate recommendations for and use of personal protective equipment and other health and safety protocols. These exposures can occur at well pads, compressor stations, transfer points, and processing plants as well as during transportation. The efficacy of current hearing protection against the types and levels of noise (which can be more hazardous when combined with vibration) associated with certain phases of OGD (e.g., drilling, hydraulic fracturing, and production) is unknown (Witter et al. 2014).

Data from the oil and natural gas industry indicate a high rate of transportation-related deaths and non-transportation physical contact deaths (see Appendix C; Mason et al. 2015b; Retzer et al. 2015). State-level data in Appalachia have suggested a similar problematic pattern of vehicular accidents related to OGD (Graham et al. 2015; Muehlenbachs and Krupnick 2013). Additional risks from OGD and earlier oil and natural gas development include exposure to high-pressure incidents (e.g., well pad blowouts), other equipment failures, corrosive liquids, and excessive heat.

A recent decrease in the death rate for the entire oil and natural gas industry (Mason et al. 2015b) represents a significant achievement in light of increased productivity, and OGD is likely to be part of that improvement, although death rates are still many times the rates of other industries and remain a target for ongoing improvement (Mason et al. 2015b).

Research Goal and Examples of Research Activities: The first goal of research would be to (1) determine whether protocols used to protect workers against noise and vibration during various OGD operations (e.g., drilling, hydraulic fracturing and work near compressor stations) are in widespread and effective use, (2) document whether the protocols are adequate for preserving the hearing of OGD workers, and (3) if necessary, conduct research to inform interventions that reduce or prevent noise and vibration exposures that might lead to acute or chronic human health effects.

The other goal of research would be to identify OGD-related causes of injuries and fatalities that occur on the well pad and off of the well pad (e.g., compressor stations and pipelines), as well as during the transportation of equipment, water, waste, and other OGD-related cargo. Studies should use methods that screen and survey worker populations over time to determine the underlying predictors of physical-hazard related injuries and deaths. Results from this research would inform workplace interventions (see question below on workplace organization) meant to protect worker health. The success of research, like much research related to workers, depends on the type of publicly available exposure data and on an investigator’s ability to access work sites where and when needed to achieve study objectives.

Topic:	**Workplace organization**
Question:	**How do workplace organization and culture affect the health and safety of OGD workers? How can industry leadership identify, select, and measure the effectiveness of interventions that can help reduce or prevent threats to worker safety and health?**

Background: OGD operations have some unique — and challenging — organizational attributes that can affect industry planning, data access by researchers, and useful intervention to protect worker safety. These attributes include reliance on many levels of contractors and subcontractors to perform routine operations, shift work schedules designed to accommodate the production schedule as well as the social needs of transient and permanent workforces, and concerns about workforce substance abuse (Goldstein et al. 2014; Maryland Institute for Applied Environmental Health 2014; Schafft et al. 2013).

The reliance on sequential contract and subcontract operators is characteristic of OGD. Teamwork between disparate corporate entities is essential to safety as workers move from site to site and provide services. Furthermore, the health and safety of workers (and the neighboring community) depends on sound health and safety planning. The variety of employers on site as well some OGD exemptions from OSHA regulations have implications for emergency planning, use of medical and social services, and researchers' access to injury and illness data, which are needed in cases where claims of chronic diseases are questioned.

Workers employed by different contracting organizations might have different health insurance availability and coverage, and it is not known whether these differences in turn cause differences in the health of workers in the industry. A key data gap is whether and to what degree formal and informal policies for reporting and documenting accidents and injuries among the various contract entities affect health and apparent rates of injuries and illnesses. Workers might feel that they should refrain from or delay reporting an injury until it is disabling (Fan et al. 2006; Witter et al. 2014).

Shift work schedules are an example of a challenging organizational attribute. Operations cannot be limited to daylight hours. Shift work schedules for a variety of operations may be based on production needs, employer convenience, workforce convenience (for a mobile workforce in which a large number of workers commute from distant homes), and on established principles of shift scheduling. Data about such schedules and how they affect the health and safety of OGD workers do not yet exist.

The effectiveness of the various kinds of employers and most-effective practices in addressing substance abuse among workers in safety-sensitive jobs is unknown. An increased focus on the safety culture of OGD worksites might improve community health along with worker health.

Research Goal and Examples of Research Activities: The goal of research would be to study the effectiveness of the various kinds of workplace organizational structures in protecting the health and safety of workers. Analysis of record-keeping requirements and exemptions could be useful for detecting and preventing workforce health issues and could benefit research planning.

3.9.3 Public Health

There is widespread concern among communities and individuals about the potential for health effects associated with OGD. Well-designed near-term and long-term studies that incorporate high-quality measures of exposure are needed to address these concerns. Near-term studies could make use of currently available data to provide information as quickly as possible. Long-term studies might be needed to address questions that cannot be answered adequately with near-term studies. Other research questions focus on specific potential exposures that might be the subject of near-term or long-term studies: water exposures, air exposures, and psychological stress.

Topic:	**Public health effects (near-term studies)**
Question:	**Are there demonstrable increases in symptom reporting, illnesses, doctor visits, accidents, or hospitalizations among community members living near OGD? Are any such indicators of health effects attributable, singly or in combination, to specific chemical, physical, or sensory stressors associated with OGD?**

Background: Uncertainty about potential short- and long-term health effects of OGD has led to community concern. Early health research has included unsystematic community surveys, systematic studies of non-random populations, and cross-sectional studies that lacked a rigorous research design or specific exposure metrics. These study limitations restricted the conclusions that could be reached (see Appendix C). Nonetheless, studies based on indirect exposure measures (e.g., distance from drilling sites or comparisons of similar communities or of communities before and after drilling) are useful for hypothesis generation even though they cannot be used to attribute effects to specific OGD-related exposures.

In addition to OGD-releated chemicals in environmental media (e.g., air, water, sediment, soil, and food), people might be exposed to physical hazards and sensory stressors. Some of these exposures are documented in communities affected by OGD, and some of the chemicals and other stressors are associated with health effects under certain exposure conditions. For example, increased noise levels and vibration can occur during various phases of OGD. At high enough exposures, noise can lead directly to hearing loss or to effects (e.g., cardiovascular disease) mediated through other mechanisms including stress pathways.

Studies of other sensory stressors might require the development or validation of new methods. The perception of odor might exacerbate symptoms or the reporting of effects but could also lead to direct effects such as decreased sense of smell, which can be measured using standardized approaches. Light at night might lead to stress, poor sleep, or other health effects. Light at night has been studied in other contexts (e.g., in studies of shift workers), but exposures and their effects are not well described in the context of OGD. Studies of potential health effects of such sensory stressors could provide the scientific basis for specific mitigation strategies such as placement of structural barriers or regulation of hours of operation or equipment placement.

Even if the impact of OGD stressors on the health of the general population proves to be minimal overall, there may be subgroups that are particularly prone to health effects. Children and adults with underlying respiratory conditions may be susceptible to acute exacerbations of asthma or decreases in respiratory function associated with short-term changes in air quality. Pregnancy, fetal development, and early childhood are known windows of susceptibility to health effects associated with exposures to certain health stressors.

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Topic:	**Public health effects (near-term studies)**
Question:	**Are there demonstrable increases in symptom reporting, illnesses, doctor visits, accidents, or hospitalizations among community members living near OGD? Are any such indicators of health effects attributable, singly or in combination, to specific chemical, physical, or sensory stressors associated with OGD?**

(continued from previous page) Socioeconomic disadvantage and associated comorbidity or lack of access to preventive medical care might interact with OGD-associated exposures and lead to increases in health effects. Finally, individuals with underlying depression or other mental health conditions might have enhanced perceptions of ill health as well as increased use of medical services for symptoms potentially linked to OGD. Identifying these vulnerable subpopulations and understanding how underlying physical and mental health conditions interact with exposures might uncover health effects that would otherwise be missed in studies focusing on the general population.

Research Goal and Examples of Research Activities: The goal of this research would be to determine, through systematic research, if individuals exposed to OGD are at increased risk for health effects. Well-designed population-based surveys and records-based studies could be used to characterize the extent and severity of health changes that might be attributable to OGD. Descriptive studies that characterize communities before and after (or with and without) OGD operations should be population-based or otherwise representative, have high response rates, use systematic and validated survey questions, and where feasible include clinical and biological measurements. Subjective health endpoints (e.g., symptoms) would require validation through the collection of medical records or biomarkers, or through other means. Although the highest quality research linking OGD to health concerns would be studies with well-characterized exposures (as described in the following two questions on water exposures and air exposures), it will take time for such exposure metrics to be developed and validated. Studies that improve on the current limited literature despite falling short of the ideal are needed today to determine the extent to which there is a problem that needs to be addressed and to generate hypotheses. Such near-term health studies should be based on hypotheses about plausible links between OGD-related exposures and specific health outcomes.

Topic:	**Public health effects (water exposure)**
Question:	**Are there health effects associated with measurable OGD-related exposures in water resources?**

Background: The scientific literature and popular press reflect concern about the potential for water contamination at various phases of OGD and for health effects associated with using contaminated water resources. Under ideal conditions and practices, exposures to contaminated water may be limited. However, safeguards can fail (e.g., wellbore integrity failure at some point over the lifetime of the well, run-off at sites that is not entirely captured, or failure of holding tanks). Water contamination has occurred in such failure situations (EPA 2015). Systematically collected data that quantify the concentrations of chemicals and radiation found in the groundwater and surface water of communities studied before, during, and after nearby OGD operations were introduced are limited. If safeguards both fail and result in OGD-related contamination of a water resource, individuals could be exposed to OGD-related stressors in water used for drinking, washing, cooking, irrigating, and showering or bathing. They might also be exposed to any OGD-related stressors that volatilize, influencing indoor air quality.

Most published research to date on the health effects of OGD has lacked specificity in terms of exposure metrics (e.g., Casey et al. 2015; Jemielita et al. 2015; McKenzie et al. 2014; and Stacy et al. 2015). Although studies have reported increased symptoms and hospitalizations in association with residence “near” OGD, research linking specific health effects to OGD-related stressor concentrations in household water that properly accounts for water consumption and other exposure opportunities has not been reported.

Research Goal and Examples of Research Activities: The goal of research would be to characterize individual-level exposures to stressors in drinking water and other household water and to link such exposures to specific health outcomes. This research would incorporate the quantitative exposure measures from the research question on water quality (see Section 3.4 above). In the absence of such high-quality exposure metrics, preliminary studies with imperfect exposure approximations could still be useful for hypothesis generation.

Preliminary research might compare selected chemicals or radioactive material in household water that are indicative of OGD (i.e., indicator species) before and after the initiation of OGD activities or in communities differentially affected by OGD. In designing such observational research, investigators should draw on methods from other disciplines to better approximate the designs of experimental research while accounting for differences in comparison communities (e.g., difference-in-differences methods; see Abadie 2005). Other designs will be needed to establish both changes in water quality over time and changes in health effects after exposure. Studies carried out in multiple settings might shed light on complex interactions between exposures, geographic and population characteristics, and health outcomes. At a minimum, studies should use a validated marker or reasonable approximation of exposure or should create opportunities to retrospectively assign exposure categories or metrics (e.g., by geocoding addresses for later linkage with geographic information system–linked databases and with data on water sources and use patterns). Methods development and validation may be required to move from characterization of surface and ground water changes caused by OGD to characterization of household water and individual exposures.

Studies should include well-defined populations (i.e., not rely on convenience samples), have sufficient statistical power, collect systematic and standardized health data, and, where appropriate, be population-based. Exposure assessment in the context of health studies would use sampling designs, selected indicator species, and knowledge of surface and groundwater characteristics and water distribution systems to develop validated exposure metrics for use in linking water-based exposures to potential health effects. Health effects of potential interest include but are not limited to changes in kidney, liver, or immune function; genotoxicity; and reproductive effects. Studies of longer-term health effects, such as increases in risk for specific cancers, may be feasible to the extent that they can be carried out using existing records or other means using cross-sectional or retrospective designs. Novel biomarkers specific to effects of exposures associated with OGD could also be incorporated.

Topic:	**Public health effects (air exposure)**
Question:	**Are there health effects associated with measurable OGD-related exposures in air, including unusually high short-term exposures?**

Background: Health effects associated with exposure to criteria air pollutants (e.g., PM, NO_x, sulfur oxides, and carbon monoxide) have been well established and include increases in all-cause mortality, cardiovascular disease, and respiratory disease. Some limited evidence also exists for potential effects on reproductive outcomes and other health endpoints (e.g., Parkinson's disease, other neurodegenerative diseases, and cancer) and for effects from other chemicals in air, such as benzene, other VOCs, and metals. Emissions resulting from OGD can lead to changes in air quality. Several recent studies have reported air quality impacts near OGD operations (see Appendix C).

The extent to which exposures to air quality changes affect the health of individuals living near OGD facilities is not known. Without targeted monitoring in place, intermittent or sporadic increases in air concentrations and variations that affect relatively small geographic areas might be missed (Brown et al. 2014). Short-term and chronic elevations in the concentrations of specific health stressors could be associated with acute events such as hospitalizations, exacerbation of underlying respiratory conditions, and subtle changes in lung function or other measures over time.

Reported associations between air quality changes and health events are weak, but typically the large size of the potentially affected population means that small relative risks can correspond to a significant number of health events. However, the low population density in many areas around OGD might make it difficult to establish statistically significant effects for outcomes such as mortality unless the research also includes a large geographic area. It might be possible to assess biological changes and other outcomes captured with continuous rather than dichotomous measures using the smaller sample sizes available at the local level.

Research Goal and Examples of Research Activities: The goal of research would be to carry out health research focused on the impact of regional and local variations in exposures to airborne stressors that can be attributed to OGD. As noted in the research question related to water exposure, a variety of research designs would be appropriate for addressing aspects of this question. Where possible, studies should incorporate state-of-the-art measurement techniques (including monitoring to capture any local or regional exposures that fluctuate or may be unusually high but that would be missed with more traditional monitoring approaches), consider linkages to medical records and surveillance data, include direct measurements of changes in lung function and other health indicators that have been associated with specific air pollutants, and, where feasible, focus on changes in lung function over time as well as on differences before and after OGD operations were initiated. Studies should incorporate relevant biomarkers of effects linked to specific air pollutants that are shown to be differentially present or elevated in association with various aspects of OGD operations. Because many factors might affect changes in lung function and other health outcomes associated with air pollution — including lifestyle factors, demographic and socioeconomic factors, medical history, past exposures, concurrent environmental and occupational exposures, and stress — studies should also take these other factors into account. Study populations of special interest would include individuals with underlying respiratory disease and other potentially vulnerable groups such as children, pregnant women and their fetuses, and the elderly.

Topic:	**Public health effects (psychological stress)**
Question:	**Do psychological stressors associated with OGD affect the health of individuals in affected communities?**

Background: Individuals experiencing job loss, other threats to their standard of living, or environmental accidents have been shown to exhibit increased levels of stress, depression, and anxiety. Stressors associated with OGD, such as increased traffic, noise, and light at night, and decreased availability of essential services in the community, might lead to chronic stress, altered stress responses, and mental health effects. Uncertainty about risks and the future might also lead to such outcomes. Evidence from multiple sources suggests that chronic stress leads to demonstrable physiologic changes and an increased risk for diseases such as depression, heart disease, asthma, and infectious diseases (e.g., Nielsen et al. 2008 and Wright 2011).

Psychological stress has been shown to alter immune function as well as inflammatory response (Cohen et al. 2012) and chronic life stress has been linked to shortened telomeres, a marker of physiologic aging (Epel et al. 2004). Chronic stress associated with exposures related to OGD might therefore explain or modify associations between such exposures and physical health outcomes. Depression and other mental health symptoms associated with such exposures might also influence the perception and reporting of symptoms and nonspecific health effects as well as the use of health care services.

Research Goal and Examples of Research Activities: The goal of research would be to understand the impact of stress and mental health symptoms on the experience of physical health outcomes in populations near OGD. Of particular interest is understanding to what extent stress or mental health conditions such as depression and anxiety contribute to any observation of exposure–health links that would not have been predicted on the basis of measured chemical levels alone. It may be especially important to study medically or socioeconomically disadvantaged populations as well as other vulnerable populations in this context (see above on near-term studies). Studies in multiple settings with appropriate control populations would be needed. Validated and standardized instruments should be used to characterize mental health status and stress. Biomarkers of stress and stress response could also be incorporated as appropriate. Health outcomes could be captured directly from interviews or clinical exams, but studies using medical records or health surveillance networks might also be informative.

Topic:	**Public health effects (long-term studies)**
Question:	**Are there long-term mental or physical health effects resulting from short-term or chronic exposures to chemical or physical stressors associated with OGD?**

Background: As noted above, uncertainty about potential long-term health effects (e.g., cancer and chronic diseases) related to OGD has led to community concern. Long-term follow-up of exposed populations can identify both lasting effects and any late effects, such as cancer or chronic diseases, that might appear only years after first exposure. Outcomes of interest might include specific cancers, specific chronic diseases, neurodegenerative conditions such as Parkinson's disease, and cognitive decline. All of these outcomes would require long follow-up intervals or repeated assessments to ascertain.

The plausibility of identifying future long-term risks depends on the magnitude of exposures and to some extent on whether shorter-term health effects or biological changes have been identified. Unfortunately, by the time such information is available, it might no longer be possible to characterize exposures or to describe baseline health characteristics in a suitable study population. However, appropriate planning and early characterization of at-risk populations, including high-quality measures of exposure, can set the stage for future prospective evaluations of long-term health effects.

Research Goal and Examples of Research Activities: The goal of research would be to set the stage for a future prospective cohort study or studies by designing current studies that will facilitate future follow-up of populations included in shorter-term studies (e.g., cross-sectional and case-control studies) or by establishing registries of individuals living near specific OGD facilities. Such efforts would include collection of some basic baseline health and demographic information as well as information needed to geocode residences for future linkages to geographic information system–linked exposure and health databases. Studies based on cost-effective options, such as virtual (passive) follow-up of a well-characterized population using medical and vital records, might be informative, as would studies based on health maintenance organizations, schools, or other closed groups.

3.9.4 Individual and Community Well-Being

The research literature suggests that OGD might contribute to a variety of social and psychosocial impacts that can negatively affect well-being for both individuals and communities.

Topic:	**Social and psychosocial effects**
Question:	**How do impacts of OGD on community-level social and psychosocial conditions vary in relation to the level and phase of development, proximity to development, land use, resource ownership, and the unique sociocultural contexts of communities?**

Background: OGD can lead to a variety of positive outcomes for some individuals and some communities — including opportunities for new and higher-paying jobs, new income opportunities for some landowners who are able to lease their land for OGD activities, and increased local business activity. At the same time, OGD has considerable potential to cause a variety of social and psychosocial impacts and disruptions — including altered patterns of interpersonal familiarity, reduced levels of social integration, and changes in interpersonal and organizational trust; increased social conflict; widespread perceptions of health and safety risks; increased individual- and community-level stress; and corrosive community relations (Brasier et al. 2011; Jacquet 2014; Ladd 2014; Perry 2012; Perry 2013).

However, little is known about the extent to which such effects might be differentially distributed across specific development situations, various community contexts, or specific subsets of local populations. For example, perceptions that OGD has or will give rise to environmental contamination and resulting health and safety risks might vary depending on the scale of development or the locations of development infrastructure in relation to residential areas. Disruptive effects on local social organization might vary across communities, depending on their patterns of historical or recent experience with resource development. Effects involving dissatisfaction, distrust, and conflict might be different in areas characterized by “split estate” patterns of land and resource ownership versus areas where landowners tend also to own the underground mineral rights. Effects might also vary across segments of local populations that vary in their likelihood of experiencing financial or other benefits associated with the development or in their access to financial and social resources — which might result in differential vulnerabilities to a variety of disruptive social and psychological effects. Information about the factors that contribute to impacts on individual-level social and psychological well-being and on community-level social organization might help local governments, service providers, and community organizations design and implement intervention strategies that could potentially reduce the severity of these impacts.

Research Goals and Examples of Research Activities: The goals of research would be to measure an array of social and psychosocial dimensions of individual and community well-being across a range of settings where OGD is occurring and to determine whether and to what extent such development might contribute to changes in well-being. Multiple well-being indicators should be measured. Examples of individual-level indicators include perceived stress levels, levels of interpersonal familiarity, perceived social integration, levels of community attachment and satisfaction, levels of trust or distrust toward other residents, levels of trust or distrust in organizations considered to have responsibility for OGD activities and decision-making, fear of crime, and perceptions of health and safety risks related to OGD activities. Examples of community-level indicators include local crime rates and trends, alcohol and substance abuse levels and trends, overall levels of participation in community activities and organizations, levels of social conflict, and the extent to which there is evidence of collective action or coordinated organizational responses directed at addressing local problems or other issues of common interest and concern.

(continued on next page)

Topic:	**Social and psychosocial effects**
Question:	**How do impacts of OGD on community-level social and psychosocial conditions vary in relation to the level and phase of development, proximity to development, land use, resource ownership, and the unique sociocultural contexts of communities?**
(continued from previous page) Research designs would need to include multiple study areas selected to represent a range of development contexts (e.g., the scale of OGD, proximity of OGD to surrounding communities, various patterns of land and mineral rights ownership, and extent of past local experience with oil and natural gas or other resource development). In addition, research designs would need to incorporate longitudinal data collection and analysis procedures to assess possible changes in well-being over time and across the phases of OGD. A mixed-methods research approach will likely be required, with possible inclusion of representative surveys of community residents and knowledgeable local key informants, qualitative interviews or focus groups, and systematic analyses of media reports and selected public data and documents.	

Topic:	**Community services and infrastructure**
Question:	**What are the impacts of OGD on community-level infrastructure and public- and private-sector service provision? How do such impacts vary in relation to the level and phase of development, proximity to development, and specific community characteristics (e.g., population size, location in relation to surrounding communities, and areas of population concentration)?**

Background: Oil and natural gas development might have impacts on an array of primarily public-sector facilities and services that are typically the responsibility of local and state government and on certain aspects of infrastructure and services that might be more closely linked to private-sector businesses and organizations. For example, there is considerable evidence that OGD is leading to impacts on road systems, traffic levels, and transportation safety in many locations (Brasier et al. 2011; Muehlenbachs and Krupnick 2013; Schafft et al. 2014). There is also evidence that some areas experience rapid growth effects associated with workforce in-migration, resulting in pressures on housing supply, public safety services, medical services, and other components of local infrastructure and service provision conditions (Brasier et al. 2011; Jacquet 2014; Williamson and Kolb 2011). However, the extent of such effects is likely highly variable. For example, the capacity of roads to accommodate large volumes of heavy truck traffic varies across areas where OGD occurs. Development occurring within reasonable commuting distances of larger cities or other areas with substantial populations would likely lead to fewer rapid growth effects and associated demands on housing, infrastructure, and services than would development that occurs in more remote areas with smaller, more isolated populations.

In addition, the nature and extent of these growth effects can be expected to vary with the scale and phase of development. They can also be expected to change over time as a result of shifting workforce characteristics and adaptive responses of local governments and other service providers. Research is needed to determine the nature of these relationships and to identify the characteristics of communities and OGD contexts likely to be most vulnerable to disruptive growth effects. Such information might improve our ability to predict probable impact levels in communities where large-scale OGD is anticipated or being initiated and to contribute to more effective responses by the relevant public- and private-sector organizations.

Research Goals and Examples of Research Activities: The goals of research would be to measure a broad array of community-level infrastructure and service provision conditions and trends across a range of settings where OGD is occurring and to determine whether and to what extent such development might contribute to reduced quality or levels of service provision or to inadequate or deteriorated infrastructure. Examples of potentially important indicators include housing availability and pricing, occurrence of substandard housing, trends in public school enrollment, traffic levels compared with the capacity of area roads and highways, rates of traffic accidents, levels of public safety and emergency-response services (e.g., police protection) compared with established standards, and demand for health care services compared with established standards. The research would need to include multiple study areas representing a range of OGD contexts (e.g., the scale of OGD activities, proximity of the activities to nearby communities, size of the nearby communities, spatial distribution of local populations, proximity of the OGD activities to regional populations, and workforce availability). In addition, the research would need to collect and analyze longitudinal data to allow assessment of possible changes in the effects of OGD activities over time and across the phases of the OGD. A mixed-methods research approach will likely be required, with possible inclusion of purposive-sample surveys of knowledgeable local key informants, qualitative interviews or focus groups, and systematic analyses of selected public and organizational data and documents.

Topic:	**Community planning and resiliency**
Question:	**How can communities better anticipate, prepare for, adapt to, and respond effectively to growth effects and other impacts of OGD?**

Background: Many communities might be poorly prepared to meet the challenges posed by OGD. This lack of preparedness might result from limited access to information about the effects of OGD and the response options, a lack of expertise and training among local public officials, legal or political restrictions on the use of local ordinances to control or manage development activities, inadequate communications between local communities and industry operators or other external organizations, limited local capacity to engage effectively in governance processes, or inadequate access to other needed resources. Research is needed to identify the most important barriers to effective community responses and the most-effective practices for enhancing the resiliency of communities that experience stressors resulting from OGD.

Lack of access to funding needed to prepare for and address impacts is one such barrier. The ability of local governments to respond to OGD-induced needs for road maintenance and improvements, expansion of public education, and increased law enforcement and other public-safety services depends on their ability to obtain the needed funding. However, there is evidence that the ability of affected communities and service providers to obtain such funding varies as a result of differing state and local policies about the levying of taxes and fees related to OGD and the distribution of funds to local governments, school districts, and other entities (Brasier et al. 2011; Jacquet 2014; Jacquet and Kay 2014; Schafft et al. 2013).

There are also questions about (1) the extent to which the timing of impacts and the availability of funds might leave communities unable to respond effectively during the period when the impacts become most critical, and (2) the mechanisms that might help to alleviate these problems. In addition, funds received by certain units of government might not be equitably distributed to the jurisdictions in which the impacts are most concentrated.

In addition, local officials and residents in some areas experiencing OGD have expressed concerns about a lack of opportunity to exercise meaningful local control over where and how OGD activities occur (e.g., an inability to apply zoning ordinances). Research has documented widespread distrust of the industry, state agencies, local governing bodies and officials, and other organizations that have control over decisions about resource development activities (Brasier et al. 2011; Jacquet 2014; Ladd 2013; Theodori et al. 2013). Research has also documented related problems of increased feelings of frustration and powerlessness among area residents and leaders as well as widespread distrust and conflict among residents who have differing views about the consequences of development in their community. Increasing local government consultation and creating opportunities for a more collaborative engagement of local residents and community leaders in decision-making about resource development, post-development planning, and impact monitoring might address the capacity of local communities to respond effectively (see Equitable Origin 2015 and ANSI/API Bulletin 100-3, Community Engagement Guidelines).

Research Goals and Examples of Research Activities: The goals of research would include a systematic identification of key barriers to effective community anticipation of, preparedness for, and adaptive response to the growth effects and other impacts of OGD on individual and community well-being. The research would also need to identify a variety of possible strategies and practices for enhancing local capacity to prepare for and respond to OGD, evaluate their potential effectiveness, and assess the feasibility of implementing these practices across a range of development settings with differing economic, social, political, and legal circumstances. A mixed-methods approach would likely be required, with possible inclusion of purposive-sample surveys of knowledgeable local key informants or expert panels; qualitative interviews or focus groups involving community leaders, planning professionals, and industry representatives; and systematic reviews of relevant state and local policies and procedures.

Topic:	**Community well-being and health effect interactions**
Question:	**In what ways and to what extent are community-level social and psychosocial impacts of OGD associated with physical and mental health consequences and increased use of medical and mental health services?**

Background: The literature about the social and psychosocial effects of large-scale resource development (and some types of technologic hazards) — as well as some literature specifically about OGD — suggests that affected populations might experience a variety of stressors as a result of disruptive changes to local social organization. Reduced levels of social integration, altered patterns of civic engagement, community conflict, decreased levels of interpersonal and organizational trust, and other structural-level changes can contribute to “corrosive” community outcomes and an overall deterioration of social capital (Jacquet 2014; Perry 2013). These effects may contribute in turn to chronic stress effects and related health outcomes. However, little is known about the ways in which stress effects and possible health outcomes might vary across communities, population segments, and OGD contexts.

As outlined earlier in the section on psychological stress, a growing literature suggests that chronic stress can lead to a range of biological changes and health effects. Conditions linked to OGD that affect local quality of life, disrupt local social organization and community relations, heighten risk perception, and contribute to feelings of powerlessness, dissatisfaction, and vulnerability among area residents might lead to increased levels of perceived stress and to measurable changes in biological stress responses. Chronic stress itself can lead to poor health either directly (by way of stress response mechanisms) or indirectly (by way of increased perceptions of health effects).

Research is needed to identify and quantify how social and psychosocial changes in communities affected by OGD might contribute to the occurrence of stress-related physical and mental health effects. If these effects occur, they might increase demands on local health care providers that might already be experiencing strains associated with workforce injuries and the kinds of development-induced growth effects outlined earlier in the section on community services and infrastructure. By identifying factors that either exacerbate or mitigate the occurrence of health effects, interventions and prevention strategies can be developed and applied.

Research Goals and Examples of Research Activities: The research would build on the data collection and analysis described earlier for social and psychosocial effects, and would collect data on the occurrence of and trends in physical and mental health outcomes in order to explore the possibility that reductions in community-level well-being may be associated with increases in physical and mental health effects. The research would include representative sample surveys of residents measuring perceived physical health and self-reported physical health symptoms, perceived stress, and perceived mental health and self-reported mental health symptoms. It would also collect and analyze aggregate-level data about the levels and patterns of diagnosis and treatment of these health issues by local health care providers. The research would need to include multiple study areas representing a range of development contexts (e.g., scale of OGD activities, proximity of the activities to nearby communities, patterns of land and mineral rights ownership, and extent of past local experiences with OGD or other resource development). In addition, the research would need to collect and analyze longitudinal data to allow assessment of possible changes in well-being over time and across the phases of OGD.

4. RESEARCH RECOMMENDATIONS

After its review and analysis of current knowledge of the potential impacts of OGD (Appendix C) and its formulation of recommended research questions (Section 3), the Committee set about to identify the highest-priority questions for moving forward.

4.1 RELATIONSHIPS AMONG RECOMMENDED RESEARCH TOPICS

The research questions fall into three general areas of research: (1) stressor and exposure characterization, (2) health and well-being assessment, and (3) evaluation of most-effective practices. The Committee recommends pursuing research in each of these areas. In particular, questions about stressor and exposure characterization are useful in addressing questions about health and well-being. Research on management practices can help prevent or reduce impacts in advance of waiting for the results of lengthy health studies.

Although the research questions cannot be pursued at the same time, they do not need to be carried out in a linear time frame. For example, all exposures do not need to be quantified before determining relationships between exposure and biological response (although both of these components are needed before quantitatively characterizing risks). However, health studies should be based on hypotheses about plausible links between OGD-related exposures and specific health outcomes. The individual research activities can be carried out in parallel and sequenced as needed to support effective analysis of exposures, risks, and health outcomes. In fact, such a parallel and sequenced execution will be crucial to achieve results in a timely fashion.

4.2 PRIORITIZING THE RECOMMENDATIONS

The Committee recognized that funding organizations, stakeholders, and researchers will have different perspectives on which research questions are most important. Some might assign priority to the research with greater relevance to the Appalachian region than to other regions. Others might assign priority to the research that can leverage work in Appalachia to answer questions nationally. Still others might assign priority to research that can provide useful results relatively quickly. Knowing this, the Committee prioritized the research questions from several perspectives, as reflected in the seven criteria presented in Section 2.

The Committee deemed all research questions to be important topics of inquiry, although not necessarily of equal importance. The questions collectively indicate knowledge gaps; they are not findings of impacts. They are broadly applicable to Appalachia and other regions, although the importance of the questions likely varies by region. Further, while the Committee's scope of review excluded OGD operations outside of the production area, the research questions are broadly relevant to OGD operations within and outside of production areas.

The Committee identified several themes that pertain to multiple research questions (Table 4-1). Throughout its deliberations, the Committee stressed the need to account properly for these cross-cutting themes in research conducted in response to the Research Agenda. The research should also contribute to an improved understanding of these themes.

Table 4-1. Cross-cutting themes that pertain to multiple research questions. These cross-cutting themes should be accounted for in studies designed in response to this Research Agenda. The research should contribute to an improved understanding of these themes.

Cross-Cutting Theme	Description
Background conditions	Many of the potential stressors associated with OGD have other sources: ▪ Natural sources (e.g., methane from biological sources or from depth by way of migration along natural fractures) ▪ Anthropogenic sources (e.g., conventional oil and natural gas development, orphaned and abandoned wells, active coal mines or abandoned mines, landfills, power plants, vehicle emissions, and long-range transport) Potential impacts attributed to OGD might have other causes: ▪ Baseline ecological characteristics and baseline human health and social characteristics must be distinguished from OGD-specific impacts.
Variability	Several factors related to levels of stressors and potential impacts can vary considerably: ▪ Spatial variability (e.g., geology, industry practice across regions, and location of OGD operations relative to surrounding communities and ecosystems) ▪ Temporal variability (e.g., changes to industry practice over time and duration of development) ▪ OGD facility variability (e.g., compressor stations and processing plants) ▪ Individual variability (e.g., human and ecological exposure and susceptibility)
Benefits of OGD	In some cases, the potential impacts of OGD could be interconnected with potential benefits. Some examples: ▪ Improvements to local infrastructure could decrease traffic injuries over the long term. ▪ Expansion of medical facilities in response to an influx of workers could improve access to healthcare.
Permitted, accidental, and unauthorized releases of stressors to the environment	Stressors entering the environment might lead to potential impacts: ▪ Stressors intentionally released in accordance with applicable regulations (e.g., permitted discharges to surface water, equipment emissions to ambient air, and vehicle emissions) ▪ Stressors released through illegal or poor practices (e.g., improper waste disposal or accidental releases of fracturing fluid and other materials)
Data availability and quality	Ready access to high-quality OGD-related data of various kinds (e.g., chemical usage, waste composition and management, and documentation of accidents) is essential to designing useful and efficient research. Some challenges to accessibility are the: ▪ Confidential nature of some information ▪ Lack of standard analytical methods for characterizing some OGD-related wastes ▪ Uneven documentation of some data Creation of standardized electronic (digital) reporting systems and databases would help facilitate ready access to OGD-related data. The Committee specifically noted the value of a standardized database to document permitted, accidental, and unauthorized releases from OGD operations.

Funding for research to answer these questions, like that for all scientific research, is limited. The Committee therefore used its criteria to identify 13 research questions of overarching importance. In Table 4-2, the topics addressed by the 13 research questions are grouped by the three general areas of research (i.e., stressor and exposure characterization, health and well-being assessment, and evaluation of management practices). Within the three general areas of research, the research topics are listed in alphabetical order and accompanied by brief descriptions. The research questions of overarching importance target a better understanding of exposure, risk, and effects from a broad spatial and substantive perspective.

4.3 SUMMARY

Based on its criteria, the Committee recommends that a research program arising from this Research Agenda focuses on the questions deemed to be of overarching importance. As noted above, these questions target a better understanding of exposure, risk, and effects from a broad spatial and substantive perspective. Collectively, answers to these questions would provide the knowledge needed to answer the most important questions about the potential impacts of OGD. Ideally, research would be pursued on topics that are addressed by the other 22 questions (Table 4-3). As noted earlier, the most important questions would likely vary by region and decision-making purpose.

This Research Agenda is intended to identify opportunities for government, the oil and natural gas industry, nongovernmental organizations, and academics to work cooperatively toward improving the understanding of potential impacts and making further advances in minimizing or preventing them. It also serves as a framework within which existing research efforts fit. In fact, there is a substantial amount of concordance between the Committee’s 35 research questions and research recommendations in the peer-reviewed literature (Appendix A) as well as overlap with ongoing research programs. The Research Agenda should therefore be implemented in careful coordination with others working actively in this area. The Committee anticipates that the Research Agenda will be used by researchers and those who fund them as well as by regulators, the oil and natural gas industry, environmental organizations, public health experts, and other stakeholders to inform policy development in this important area.

Table 4-2. Topics addressed by the 13 research questions of overarching importance (1).

Research Topic	Summary
Stressor and Exposure Characterization (2)	
Chemical toxicity (human and ecological)	Adequate toxicity information does not exist for some components of OGD fluids and wastewater. The initial goal of research would be to improve the understanding of the composition of these fluids. The goal of subsequent research would be to conduct toxicological evaluations where exposure information suggests that such evaluations would be helpful to decision-making about the protection of human and ecological health.
Emissions and air quality	OGD emissions might affect air quality. The goal of research would be to quantify the contribution of emissions from OGD to concentrations of a wide range of air pollutants.
Total human exposure	People might be exposed to a range of OGD-related health stressors, depending on the effectiveness of industry and regulatory protocols. The goal of research would be to identify these exposures and, for any of potential concern, to use rigorous methods to quantify them.
Water quality	Reports of surface water and groundwater contamination allegedly caused by OGD have garnered much public attention. The goal of research would be to quantify any contribution of OGD to short- and long-term trends in the quality of water resources.
Health and Well-Being Assessment (2)	
Ecological health effects (landscape change)	OGD can result in physical (e.g., habitat fragmentation) and sensory (e.g., increased light) changes to landscapes. The goal of research would be to quantify the contribution of OGD to short- and long-term landscape changes and any resulting ecological risks.
Public health effects (air exposure)	Emissions associated with OGD might lead to changes in air quality. The goal of research would be to determine whether variations in OGD-related airborne exposures are associated with health effects; these studies would focus on any quantified exposures of concern from high-quality studies of potential OGD impacts on air quality.
Public health effects (water exposure)	The scientific literature and popular press reflect concern about OGD-contaminated water resources. The goal of research would be to conduct population-based studies of health effects; these studies would focus on any quantified exposures of concern from high-quality studies of potential OGD impacts on water resources.
Public health effects (near-term studies)	Uncertainty about potential short- and long-term health effects related to OGD has led to community concern. The goal of research would be to determine, through systematic research, whether nearby communities are at increased risk for health effects that might be plausibly linked to OGD-related exposures. If an increased risk is identified, further research would then investigate in greater detail how and to what extent any such health effects are attributable to OGD-related stressors.
Social and psychosocial effects	OGD might have social and psychosocial impacts. The goal of research would be to determine whether and to what extent OGD might contribute to changes in individual and community well-being.
Worker health effects (chemical and radiation)	The OGD work environment can involve various health stressors, with exposure dependent on use of health and safety protocols. The goal of research would be to characterize and identify techniques for mitigating acute and chronic exposures of potential concern that are not already addressed by industry and regulatory protocols.
Evaluation of Most-Effective Practices (2)	
Accidental releases	OGD-related fluids and wastes can be released to the environment as a result of spills, leaks, blowouts, and other accidents. The goal of research would be to understand the nature of potential impacts from the accidental releases and how they might be prevented or reduced.
Permitted waste management	OGD generates solid and liquid wastes (e.g., produced water, drill cuttings, and drilling fluids). The goal of research would be to determine the potential for impacts from approved disposal of OGD wastes and the most-effective practices for managing the wastes.
Wellbore integrity	A tremendous amount of guidance exists to support the planning, design, and execution of well construction to prevent gas and fluids from escaping the wellbore. The goal of research would be to determine whether guidance is being broadly and effectively implemented and is sufficient to ensure the lifetime integrity of wellbores as OGD technology and practices evolve.

(1) The cross-cutting themes in Table ES-1 should be accounted for in studies designed in response to this Research Agenda. The research should contribute to an improved understanding of these themes.
(2) Within each category, research topics are listed in alphabetical order.

Table 4-3. The Committee's prioritized research questions by topic.

General Area of Research	Purpose	Research Topic (1)
Stressor and Exposure Characterization	To improve understanding of whether exposures of potential concern are occurring	**Topics of Overarching Importance (2)** ▪ Chemical toxicity (human and ecological) ▪ Emissions and air quality ▪ Total human exposure ▪ Water quality
		Other Important Topics ▪ Climate-forcer emissions ▪ Criteria air pollutants ▪ High-emitters ▪ Human biomonitoring ▪ Indoor air radon ▪ Induced seismicity causes ▪ Water use ▪ Water-quality diagnostics
Health and Well-Being Assessment	To improve understanding of whether potential impacts on public and worker health, ecological health, and well-being are occurring	**Topics of Overarching Importance (2)** ▪ Ecological health effects (landscape change) ▪ Public health effects (air exposure) ▪ Public health effects (near-term studies) ▪ Public health effects (water exposure) ▪ Social and psychosocial effects ▪ Worker health effects (chemical and radiation)
		Other Important Topics ▪ Community services and infrastructure ▪ Community well-being and health effect interactions ▪ Ecological health effects (chemical and radiation) ▪ Ecological health effects (cumulative) ▪ Public health effects (long-term studies) ▪ Public health effects (psychological stress) ▪ Worker health effects (noise, vibration, and physical hazards)
Evaluation of Most-Effective Practices	To enhance practices that minimize or prevent impacts	**Topics of Overarching Importance (2)** ▪ Accidental waste release ▪ Permitted waste management ▪ Wellbore integrity
		Other Important Topics ▪ Air quality control ▪ Community planning and resiliency ▪ Ecological health effects (mitigation) ▪ Induced seismicity prevention ▪ Water transport ▪ Wellbore diagnostics ▪ Workplace organization

(1) Within each category, research topics are listed in alphabetical order.

(2) The Committee identified 13 research questions of overarching importance, which target a better understanding of potential exposure, risk, and effects from a broad spatial and substantive perspective.

5. IMPLEMENTATION OF THE RESEARCH AGENDA

In this Research Agenda, the Committee has formulated a comprehensive and prioritized set of key research questions designed to find answers about the potential impacts of OGD on human health and well-being, communities, ecological health, and the environment. This Research Agenda is intended to help guide timely, high-quality implementation of the highest-priority research. The findings should inform decision-making such that the potential benefits of OGD can be maximized while the potential adverse impacts are minimized or prevented. The achievement of these goals will require three principal steps:

- Organize the research program for maximum quality, credibility, and impact;
- Identify the funding needed to implement, produce, and disseminate the research; and
- Establish and follow a timeline for implementing the most time-sensitive research.

5.1 TIMELINE

In practical terms, the implementation of a program of high-priority research requires choices about which research questions can be pursued right away and which can only be pursued later, after the necessary data and information are obtained from the earlier research.

The research needed to address some of the human and ecological health issues, for example, is outlined in Figure 5-1 as a series of phased steps over time. Certain research activities (e.g., the detailed exposure assessments and enhanced near-term health and ecological impact studies using existing data) could begin immediately. Others (e.g., the long-term, higher-quality impact studies) would involve careful initial planning and could then be fully implemented once the detailed exposure assessments are under way.

Other research activities (e.g., the laboratory and field toxicity studies) could be implemented in parallel with the detailed exposure assessments. They could be conducted in time to feed into both the near-term decisions and the design of the long-term human and ecological impact studies. Once the research efforts have been organized and funding has been obtained (see following sections), the timeline would be used as the strategic action plan for getting the research under way.

5.2 ORGANIZING FOR QUALITY AND CREDIBILITY

High-quality research can be obtained in a number of ways. Given the complex and often controversial circumstances in which OGD is taking place, implementation of the Research Agenda will be most credible to a broad range of stakeholders if it is funded and overseen in a manner that leads to research of the highest quality, impartiality, and relevance.

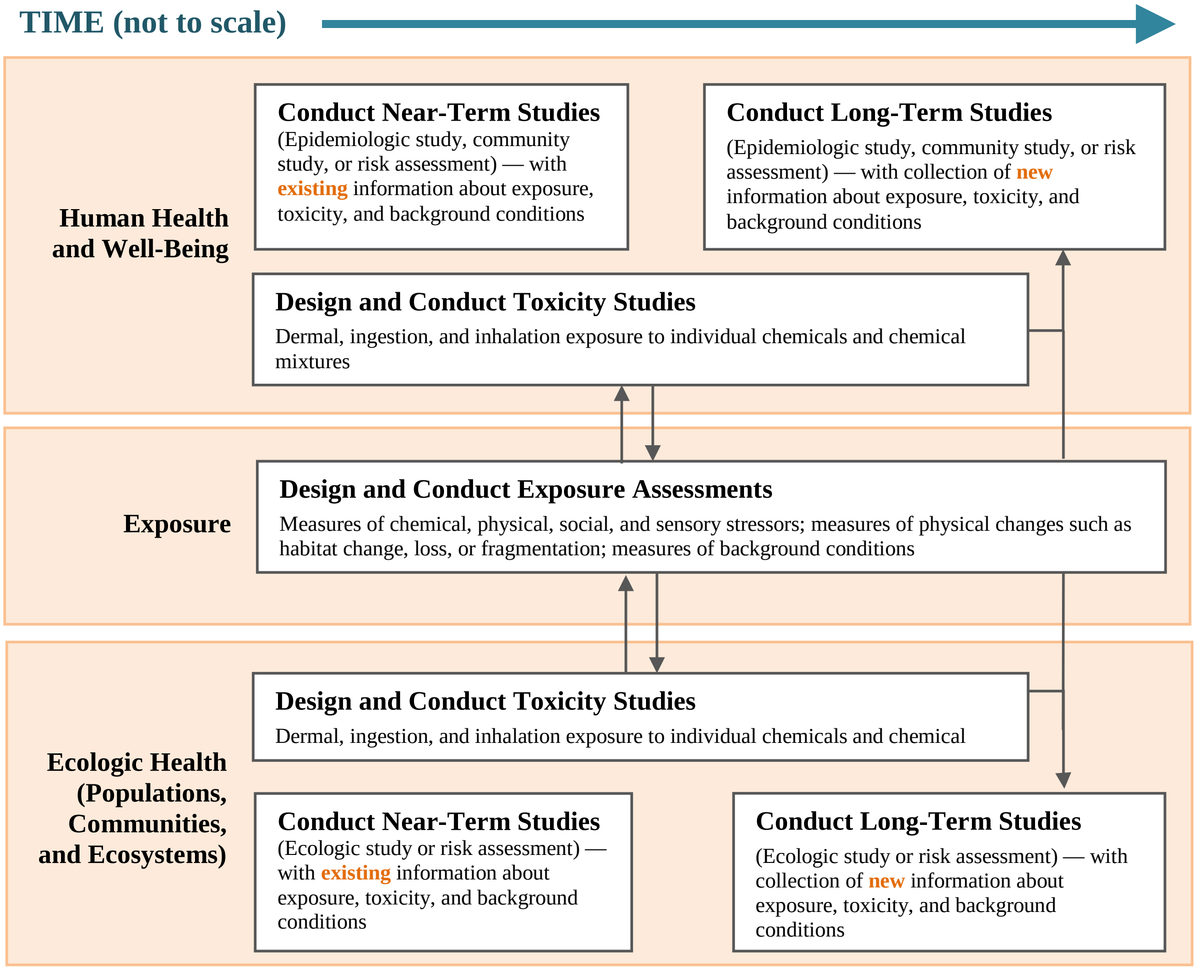

Figure 5-1. An example of research activities that will need to be sequenced.

The success of the effort will depend strongly on cooperation among government, industry, and other stakeholders to create an environment of trust in which research can be conducted and the results can be relied on to support sound decision-making. This approach depends on four elements:

- Governance and Funding: Governance of the research program should be independent of its sponsors or other interested parties and be managed by an impartial research organization. Core funding should be balanced with sponsorship by industry, government, and possibly foundations and other sources. Ideally, funding should be provided for institutional and long-term support in the fulfillment of the Research Agenda outlined here and for other research topics and needs as they arise.
- High-Quality Science: The research should be overseen by a research committee and a review committee, each composed of leading scientists in various fields relevant to the Research Agenda. Members should be vetted to ensure that the research and review of results are carried out impartially. The research committee should competitively select studies for funding. The review committee, having no involvement in the selection, design, or oversight of the studies, should comprehensively review the studies for quality and technical rigor.

- No Advocacy: The mission of this independent research effort should be to produce the best science needed to make better informed decisions, without advocating policy positions.
- Communication: The research organization should communicate results widely and transparently, make the underlying data available, and disseminate comprehensive reports — including all results, both positive and negative — to the widest possible audience at no cost.

A key challenge, given the existence of numerous research questions in a period of potentially rapid growth in OGD, will be to ensure the prompt startup of the research program proposed here, with a strong emphasis throughout on streamlining every part of the program to provide the shortest possible turnaround in obtaining answers to the key questions to protect human and ecological health. The need for timely results would also argue for relying, as far as possible, on existing research organizations to expedite implementation.

5.3 FUNDING

The success of this comprehensive Research Agenda will depend strongly on the identification of significant and balanced funding and careful coordination with ongoing research efforts, such as the federal Multi-Agency Collaboration on Unconventional Oil and Gas Research and the National Institute of Environmental Health Sciences. Although the Committee was not charged with specifying detailed budgets for the research program, it made the following three funding recommendations in support of the successful implementation of the Research Agenda:

- The Committee recommends, and hopes, that elements of the Research Agenda will be taken up as priorities for funding by appropriate government agencies, such as the National Institute for Occupational Safety and Health (NIOSH) for worker health effects and the Department of Energy National Energy Technology Laboratory for wellbore integrity and other topics that overlap its research portfolio (National Energy Technology Laboratory 2015).
- The Committee recommends that some of the high-priority exposure and impact studies be funded and implemented as integrated research programs — that is, as programs whose elements are funded as a whole and executed in parallel (as shown in Figure 5-1) instead of being separately funded by disparate organizations.
- In pursuit of such integrated research programs, the Committee recommends, and hopes, that government and industry entities might choose to identify a major portion of this Research Agenda for funding, such as the overarching human exposure and health topics. Such funding can provide the impetus for establishing a new, integrated research program to specifically address those questions.

In view of the importance of implementing the Agenda as quickly as possible, HEI has already begun an active program of outreach to key potential partners and sources of funding from government, industry and the foundation community.

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ABBREVIATIONS

API	American Petroleum Institute
BLM	Bureau of Land Management
BTEX	benzene, toluene, ethylbenzene, and xylenes
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
NIOSH	National Institute for Occupational Safety and Health
NO_x	nitrogen oxides
NORM	naturally occurring radioactive materials
OGD	oil and natural gas development
OSHA	Occupational Safety and Health Administration
PA DCNR	Pennsylvania Department of Conservation and Natural Resources
PAHs	polyaromatic hydrocarbons
PM	particulate matter
VOCs	volatile organic compounds

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APPENDIX A: SUMMARY OF RESEARCH RECOMMENDATIONS FROM OTHER ORGANIZATIONS

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

SUMMARY OF RESEARCH RECOMMENDATIONS FROM OTHER ORGANIZATIONS

There continues to be debate about the potential impacts of OGD in the peer-reviewed scientific literature, in governmental and nongovernmental reports, in the communities experiencing development, and in the press. Although additional peer-reviewed studies have been published in recent months, the Committee found 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. To help with identification and prioritization of research needs, the Committee assembled recent recommendations from peer-reviewed scientific literature and reports from non-governmental research organizations, industry, and governmental agencies. Table A-1 captures the essence of these recommendations; more detailed information can be found in the cited publications. The table includes a limited number of peer-reviewed articles and reports that were available as of August 2015.

Table A-1. Summary of recent research recommendations from the peer-reviewed scientific literature and reports from industry, non-governmental research organizations, and governmental agencies (as of August 2015). Recommendations are not reported verbatim and have been generalized in many cases.

WELLBORE INTEGRITY
Assess wellbore integrity throughout the lifetime of wells that are hydraulically fractured[1,15,21,27]
Identify materials for improved wellbore design, construction, testing, and remediation[1,15]
Assess whether current engineering practices are sufficient to prevent against potential releases of OGD-related stressors to the environment[1,15, 26]
AIR QUALITY
Characterize and model emissions and air quality changes during specific phases of development (e.g., drilling and hydraulic fracturing)[1,3,5,15,25,26,27]
Establish emissions inventories[1,3,15]
Characterize baseline air quality[1,2,3,4,5,6,8,9,11,15,19,22,26,27]
Develop methods to continuously measure emissions (allowing for the identification of periods of extreme exposure), account for local weather conditions, and detect chemical mixtures near OGD[25]
WATER QUALITY AND USE
Characterize baseline water quality and monitor over well lifetime[1,2,4,5,6,8,9,11,15,18,19,22,23,24,26,27]
Determine fate and transport of fracturing-related fluids in the subsurface [2,6,15,18,22,23]
Assess cumulative impacts on water resources over well lifetime[4,9,19,22,27]
Determine the likelihood of aquifer contamination caused by subsurface migration[1,6,22,27]
Determine the severity of erosion and siltation resulting from OGD[9,22]
Identify signature chemicals associated with OGD that could be used for water quality monitoring[1,15,23]
Predict and measure the quantity and impacts of water withdrawal, particularly in arid or low-flow regions[1,4,9,11,15,23,24]
Develop new technologies to reduce water use[1,15,22]
Investigate the role of orphaned and abandoned wells in the migration of OGD-related gas and fluid[8,18,21,27]

(table continued on next page)

Table A-1. Summary of recent research recommendations from the peer-reviewed scientific literature and reports from industry, non-governmental research organizations, and governmental agencies (continued)

WASTE MANAGEMENT
Determine the physical and chemical characteristics of oil and gas wastewater (flowback and produced water)[1,2,6,8,11,22] and solid waste[11,22]
Determine the safest and most effective methods to manage and treat OGD-related waste (solid and liquid) in various regions (e.g., Marcellus Shale and Barnett Shale)[2,6,18,22,24,26]
Assess the environmental risks resulting from accidental releases of wastewater[18]
Study the occurrence and severity of wastewater spills[2,20,22]
INDUCED SEISMICITY
Assess the potential for induced seismic events from wastewater disposal via deep-injection wells[1,11,15,17]
Determine methods to mitigate OGD-related seismic events[1,11,15,17]
Test for preexisting fault systems at deep-well injection sites; associate various factors (e.g., temperature and pressure) with the size and incidence of seismic events[1,17]
HUMAN EXPOSURE AND HEALTH RISK ASSESSMENT
Determine magnitude and duration of exposure to stressors in air, water, and other environmental media[2,5,11,15,27]
Conduct biomonitoring of a representative population for biomarkers of exposure to OGD-related stressors[14]
CHEMICAL TOXICITY (HUMAN AND ECOLOGICAL)
Identify hazardous physical and chemical constituents in fracturing fluid and produced water[2,6,22,23]
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[6,23]
ECOLOGICAL HEALTH
Conduct spatial analysis of habitat loss or fragmentation[4,9,11,13]
Model and assess impacts on vulnerable or sensitive species and habitats[4,9,15,27]
Assess the impacts of aquifer contamination (e.g., gas and 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[9,15,27]
Determine ecological thresholds to minimize impacts (e.g., well count, forest loss, and toxicity)[4,22]
Collect baseline data on aquatic and terrestrial habitats[4,22,27]
Study habitat impacts of noise and light pollution[19]
Determine effectiveness of ecosystem protection and conservation strategies[2,27]
Determine the frequency and effectiveness of partial and full well pad reclamation[19]
WORKER HEALTH
Characterize worker exposure to air and water toxics (e.g., diesel exhaust, fracturing chemicals, silica, and H_2S), noise, and naturally occurring radioactive materials[5,10,12,15,26,27]
Conduct disease surveillance in defined worker populations[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 underreporting[12]
(table continued on next page)

Table A-1. Summary of recent research recommendations from the peer-reviewed scientific literature and reports from industry, non-governmental research organizations, and governmental agencies (continued)

PUBLIC HEALTH
Assess the relationship between potential exposures and the spatial and temporal distribution of health outcomes in areas experiencing OGD[8,10,14]
Perform environmental epidemiology studies to evaluate whether OGD-related exposures are associated with adverse health outcomes (e.g., cardiovascular disease [air] and birth defects [groundwater])[6,8,15,26]
Characterize sensory (odor, noise, and light) stressors and links to health effects[5,6,26]
Conduct health impact assessments of OGD, particularly in rural areas with limited data on baseline disease prevalence[11,26]
Examine the relationship between OGD-related psychosocial changes (e.g., stress) and health effects[5,7,11]
INDIVIDUAL AND COMMUNITY WELL-BEING
Seek community input in the design and completion of ecological, human health, and psychosocial research[5,6,8,22]
Identify the extent and severity of traffic-related impacts[7,11,16,26]
Document legacy economic and social impacts[7,11,13,26,27]
Monitor the impact of OGD on housing cost and property values as the market evolves[13,16,27]
Determine the impact of OGD on local infrastructure (e.g., healthcare services)[6,8]
OTHER
Develop regional specific predictions of future oil and natural gas development scenarios[1,5,7,15,23]
Determine the general efficacy and environmental impacts of well re-fracturing[1,2,4,15,27]
Create inventory of orphaned and abandoned wells[3]
NOTES
[1]Jackson et al. 2014; [2]Goldstein et al. 2014; [3]Moore et al. 2014; [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]Resources for the Future 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; [23]U.S. Environmental Protection Agency 2015; [24]Rodriguez and Soeder 2015; [25]Brown et al. 2014; [26]New York State Department of Health 2014; [27]Graham Sustainability Institute 2015

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APPENDIX B: BIBLIOGRAPHY

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

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APPENDIX C: SUMMARY OF LITERATURE ON THE POTENTIAL IMPACTS OF 21ST CENTURY OIL AND NATURAL GAS DEVELOPMENT IN THE APPALACHIAN REGION AND BEYOND

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

APPENDIX C: POTENTIAL IMPACTS

Evidence for potential human and ecological exposures to stressors from OGD is shown in a series of flow diagrams (summarized in Figure C-1) and is reviewed in this section. The Committee illustrated the exposure pathways that it considered, regardless of their likelihood or significance for human or ecological health. Summaries of what is known about the potential or actual impacts on ecological health, human health, and well-being that result from these potential exposures are in Sections C.2, C.3, and C.4, respectively.

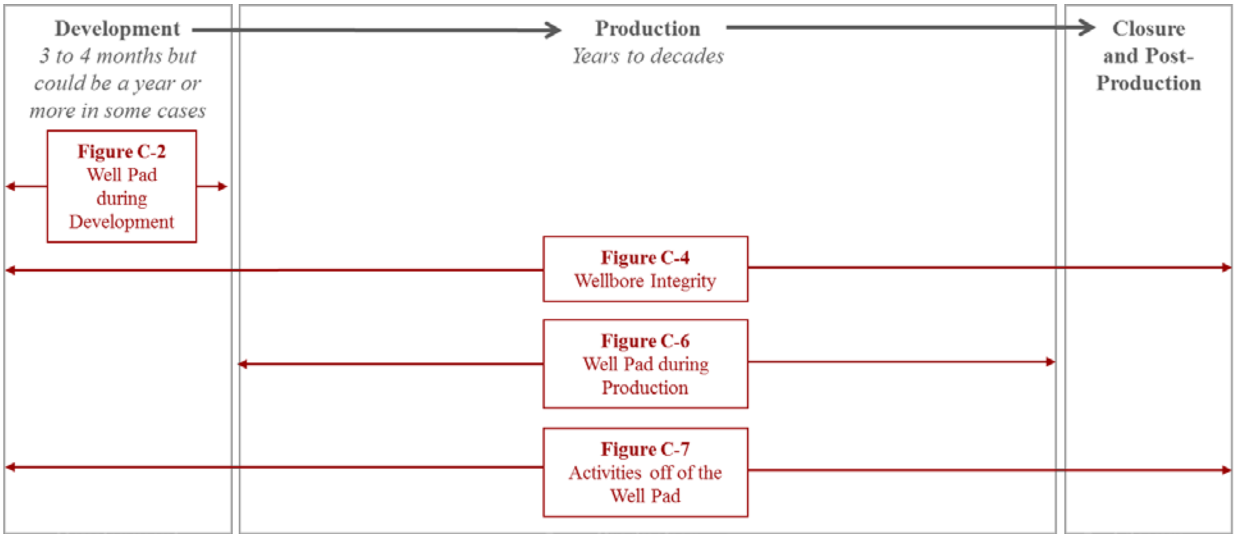


Figure C-1. Summary of flow diagrams illustrating potential exposure pathways.

C.1 POTENTIAL EXPOSURES

This section summarizes how activities on and off the well pad during development, production, closure, and post-production might result in people or ecosystems being exposed to OGD-related health stressors. The discussion is organized by operational phase, although some exposures (e.g., involving air quality) might persist across multiple phases. A number of recent reviews have summarized the state of knowledge on air (e.g., Moore et al. 2014) and water (e.g., Brantley et al. 2014; U.S. Environmental Protection Agency [EPA] 2015) exposures associated with OGD activities.

C.1.1 Exploration

During the exploration phase, geophysical testing is used to determine target formation characteristics (e.g., depth and thickness) and geologic structures (e.g., fractures and faults) to support efficient siting of well pads and regional gas-support infrastructure. One such geophysical testing method is seismic reflection surveying, which produces a three-dimensional image of subsurface geological formations by measuring seismic wave vibrations that are propagated into the earth using vibrators mounted on trucks or shallow explosive charges and reflected back to the surface. Images from these surveys expose the naturally occurring structure (e.g., faults and folds) in the rock formations. The exploration phase can involve several stressors, including noise, vibration, vehicle emissions, and landscape changes that might persist for relatively brief periods.

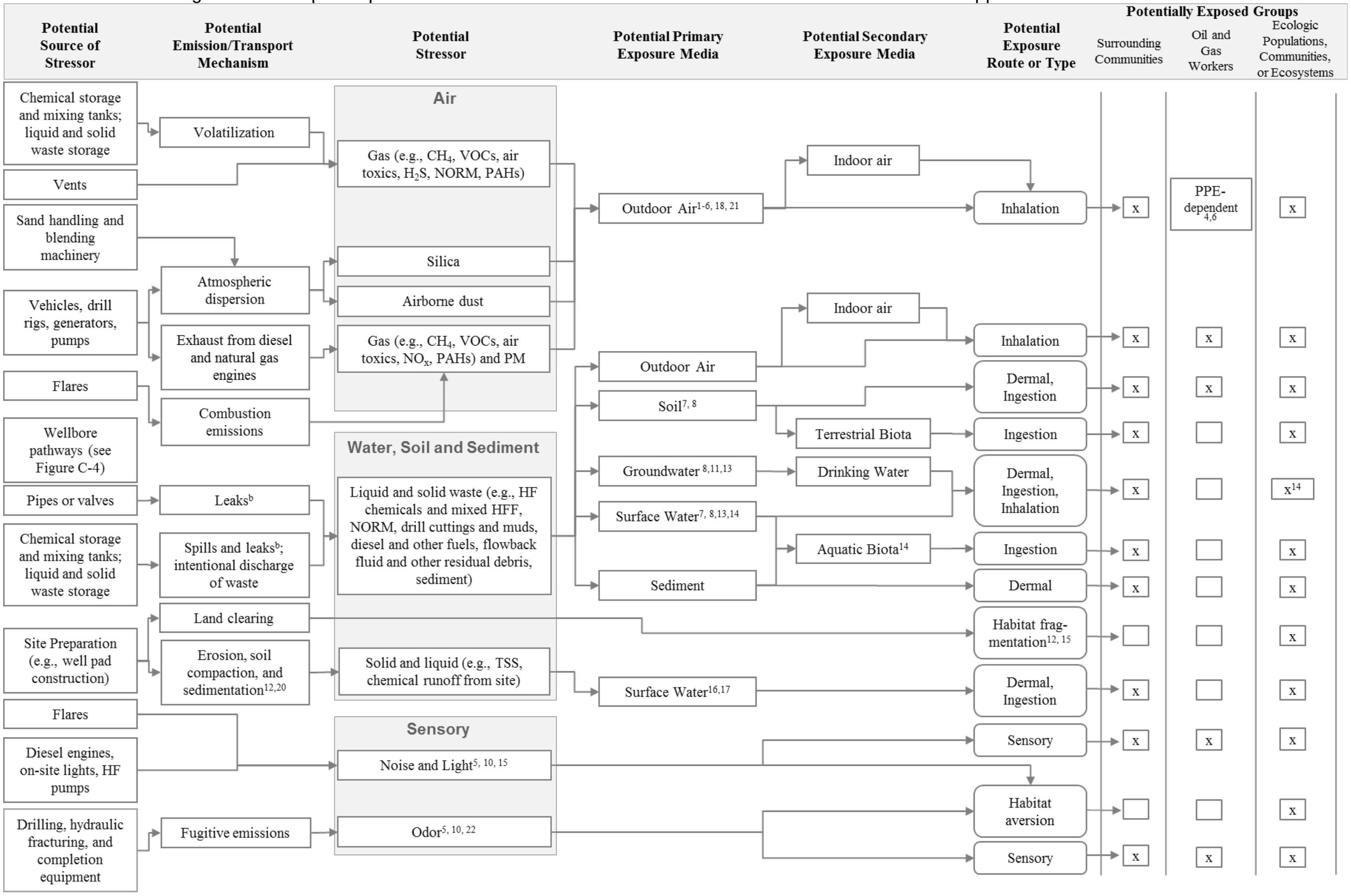
C.1.2 Site Preparation

Once a well location is chosen, site preparation and construction of the well pad and other associated infrastructure begins. Figure C-2 summarizes exposure pathways that might arise at a well pad during the development phase, beginning with site preparation through well completion. The pathways are organized by medium of exposure (e.g., air) or type of exposure (e.g., sensory). Existing site selection tools, such as Environmentally Friendly Drilling’s Land Use Site Selection Information Tool and The Nature Conservancy’s EnSitu, are currently being developed to help operators plan and manage well sites, pipelines, and other infrastructure.

Landscape change. OGD well pads in the Appalachian region have typically been constructed on 3 to 7 acres of land; roads and other associated infrastructure require an additional 7 to 9 acres (Johnson et al. 2010; Brittingham et al. 2014). As with other large-scale industrial construction projects, changes in land cover during well pad construction can lead to soil erosion and habitat fragmentation. Oil and natural gas infrastructure has been constructed on a variety of landscapes, including agricultural land, core forest habitat, and lands whose soils have a high risk for erosion and sedimentation (Drohan et al. 2012; Pennsylvania Department of Conservation and Natural Resources [PA DCNR] 2014). Well pad construction has been related to changes in dynamic soil properties (e.g., bulk density, soil organic carbon, nitrogen, and phosphorus pools) in soils that have been disturbed by the development (Fink and Drohan 2015). Early in the development of the Marcellus shale, erosion-related violations outnumbered other environmental violations, including spills and site restoration (Rahm et al. 2015). However, the average number of erosion violations per 100 unconventional wells drilled in Pennsylvania has decreased in recent years (Figure C-3).

Some studies have suggested that runoff related to OGD may be linked with increased levels of turbidity (Entrekin et al. 2011) and total suspended solids (Olmstead et al. 2013) in streams in the Marcellus region.

Figure C-2. Potential exposure pathways related to operations on the well pad during the development phase[a]. All pathways considered by the Committee are shown regardless of their likelihood or significance. Superscripted numbers indicate a reference that can be found at the end of this Appendix.



[a]Pathways related to water quantity, community well-being, and the exploration phase are not depicted.

[b]For spills, leaks, and other discharges that originate beyond the well pad, refer to Figure C-7

☒ Potential exposure PPE Personal protective equipment

HF= Hydraulic fracturing
HFF= Hydraulic fracturing fluid
H_2S= Hydrogen sulfide
CH_4= Methane
NORM= Naturally occurring radioactive material
NO_x= Nitrogen oxides
PM= Particulate matter
PAHs=Polyaromatic hydrocarbons
TSS= Total suspended solids
VOCs= Volatile organic compounds

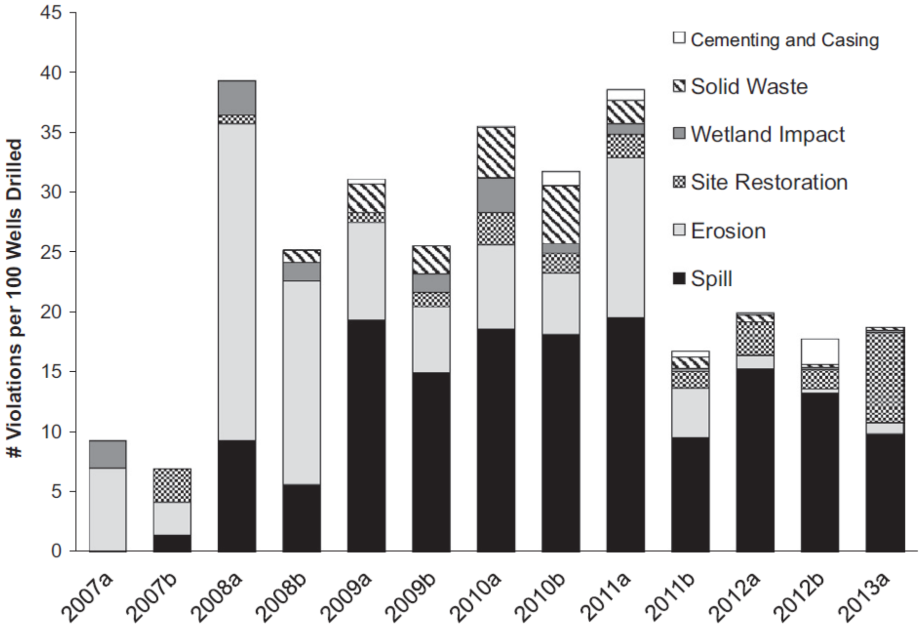


Figure C-3. Number of environmental violations per 100 unconventional wells drilled in Pennsylvania. The “a” and “b” designations refer to the first six-month period and the second six-month period, respectively, in each year. Reprinted from Rahm et al. 2015 with permission from Elsevier.

Air emissions. Diesel engines that power trucks and the equipment used for site preparation emit nitrogen oxides (NO_x), particulate matter (PM), air toxics[1], volatile organic compounds (VOCs), polyaromatic hydrocarbons (PAHs), and methane (CH_4) (Table C-1; Moore et al. 2014). Well pad construction, truck traffic, and other on-pad activities can also generate PM by resuspending dust.

Sensory stressors. Noise is present on the well pad during the development phase, beginning with site preparation. In some instances, construction equipment (e.g., excavators and backhoes) used for site clearing has exceeded acceptable day-time noise levels (New York Department of Environmental Conservation [NYSDEC] 2015). The presence of such equipment is usually temporary (NYSDEC 2015).

C.1.3 Drilling and Well Completion

Air emissions. Diesel and natural gas engines that power trucks and other equipment used for transporting material, drilling, and hydraulic fracturing emit CH_4, NO_x, air toxics, VOCs, PAHs, and PM (Table C-1; Moore et al. 2014). Natural gas engines generally have much lower emissions than diesel engines not equipped with exhaust aftertreatment technologies, such as diesel particulate filters and selective catalytic reduction units. Therefore, fuel switching has been proposed as an emission reduction strategy (e.g., Environmentally Friendly Drilling’s PbNG savings calculator). Diesel engines equipped with aftertreatment technologies have low

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[1] 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*).

emissions, comparable to natural gas engines. Existing regulations require aftertreatment technologies for on-road but not off-road diesel engines.

Venting and fugitive emissions during the drilling, hydraulic fracturing, and completion phases emit CH_4 (Caulton et al. 2014; Allen et al. 2013), VOCs, air toxics (Field et al. 2014), and potentially hydrogen sulfide (H_2S). Well completion events, in particular, have the potential to emit more CH_4 than other source activities such as pneumatic device vents (Allen 2014). However, recent EPA rules require reduced-emission completions (also called green completions) that reduce such emissions (EPA 2012; Allen et al. 2013). Flaring of flowback vapors can emit CH_4, NO_x, air toxics, VOCs, and PM (Table C-1; Moore et al. 2014; Jackson et al. 2014).

Dust resuspension can continue during this phase as a result of compressed air drilling and vehicle traffic. The total emissions and relative importance of the various source categories are expected to vary based on both the target formation and advances in technology. These emissions have the potential to affect air quality.

PAHs have been measured in outdoor air near active natural gas extraction sites[2] (Colborn et al. 2014; Paulik et al. 2015). Recent work by Goetz et al. (2015) found few emissions of non-alkane VOCs at Marcellus fencelines. Regional air quality impacts can be caused by emissions of ozone precursor gases (NO_x and VOCs) and fine PM (PM with an aerodynamic diameter of $\leq$2.5 µm [$PM_{2.5}$]) from oil and natural gas operations (Vinciguerra et al. 2015; Roy et al. 2014). Limited work has measured air quality impacts related to distinct activities such as drilling, hydraulic fracturing, and completion (Goetz et al. 2015).

Table C-1. Principal air emission sources during the development of an OGD well pad.

Source Category	NO_x	VOCs	PM	Air Toxics	Climate Forcers[a]
Diesel engines in drill rigs, frac pumps, trucks, generators, etc.	●	●	●	●	●
Natural gas engines in drill rigs, frac pumps, vehicles, generators, etc.	●	●	●	●	●
Airborne dust from vehicle traffic, site construction, etc.			●		
Fugitive emissions during drilling, hydraulic fracturing, and completion		●		●	●
Completion venting		●		●	●
Storage tanks and waste impoundments		●		●	●
Flares	●	●	●	●	●

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

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[2] Active natural gas extraction sites were defined by Paulik et al. (2015) as wells that are in the drilling, drilled, or production phases.

Exposure to respirable crystalline silica and VOCs has been characterized to some extent for oil and natural gas workers during the completion phase. Studies by the National Institute of Occupational Safety and Health (NIOSH) (Esswein et al. 2013; Esswein et al. 2014) have suggested that the potential for exposure to silica and VOCs exists for specific tasks (e.g., flowback gauging or operation of sand handling machinery) and needs to be mitigated. The Occupational Safety and Health Administration (OSHA), among other organizations (e.g., American Petroleum Institute [API] and NIOSH), has published guidelines for preventing occupational hazards related to OGD (OSHA 2014).

Accidental releases related to the wellbore. Accidental release of wellbore contents as a result of drilling, hydraulic fracturing, pre-existing pathways, or well failures could lead to human and ecological exposures. Potential exposure pathways related to the wellbore are illustrated in Figure C-4 and organized by potential emission/transport mechanism (rather than by medium or type of exposure).

Oil and natural gas wellbores have been known to fail as a result of poor engineering practice or exposure to deleterious chemical or physical conditions over time (Davies et al. 2014; Ingraffea et al. 2014; Jackson et al. 2014; King and King 2013; Dusseault et al. 2000). A review of existing data on wellbore integrity failure rates in Pennsylvania, the Gulf of Mexico, the U.S., and Norway, among other countries, can be found in Davies et al. (2014). Near the surface, failures of wellbore integrity can result in leaks of gas or liquid across or up the wellbore. Gas or brine[3] from shallow strata can also migrate along pathways between outer casings and rock formed as the result of inadequate cement sealing (Davies et al. 2014; Jackson et al. 2014). These wellbore failures and anthropogenic pathways might adversely affect air quality or groundwater quality (Llewellyn et al. 2015; Davies et al. 2014). Open-hole drilling (prior to casing installation) could also result in changes to groundwater chemistry (King and King 2013).

The potential relationship between OGD and CH_4 in adjacent drinking water wells has been the topic of debate in recent years (Siegel et al. 2015; Jackson et al. 2014; Sharma et al. 2014). A number of studies have suggested that OGD may be the source of increased CH_4 in potable groundwater (Llewellyn et al. 2015; Darrah et al. 2014; Jackson et al. 2014; Osborn et al. 2011; Molofsky et al. 2013) and surface water (Heilweil et al. 2015). However, few studies have linked CH_4 concentrations in groundwater, surface water, soil, and other environmental media with specific migration pathways (Figure C-5) related to wellbores in the development and production phases (EPA 2015). Complicating these studies is the reality that other natural and anthropogenic sources of gas and brine exist (Baldassare et al. 2014).

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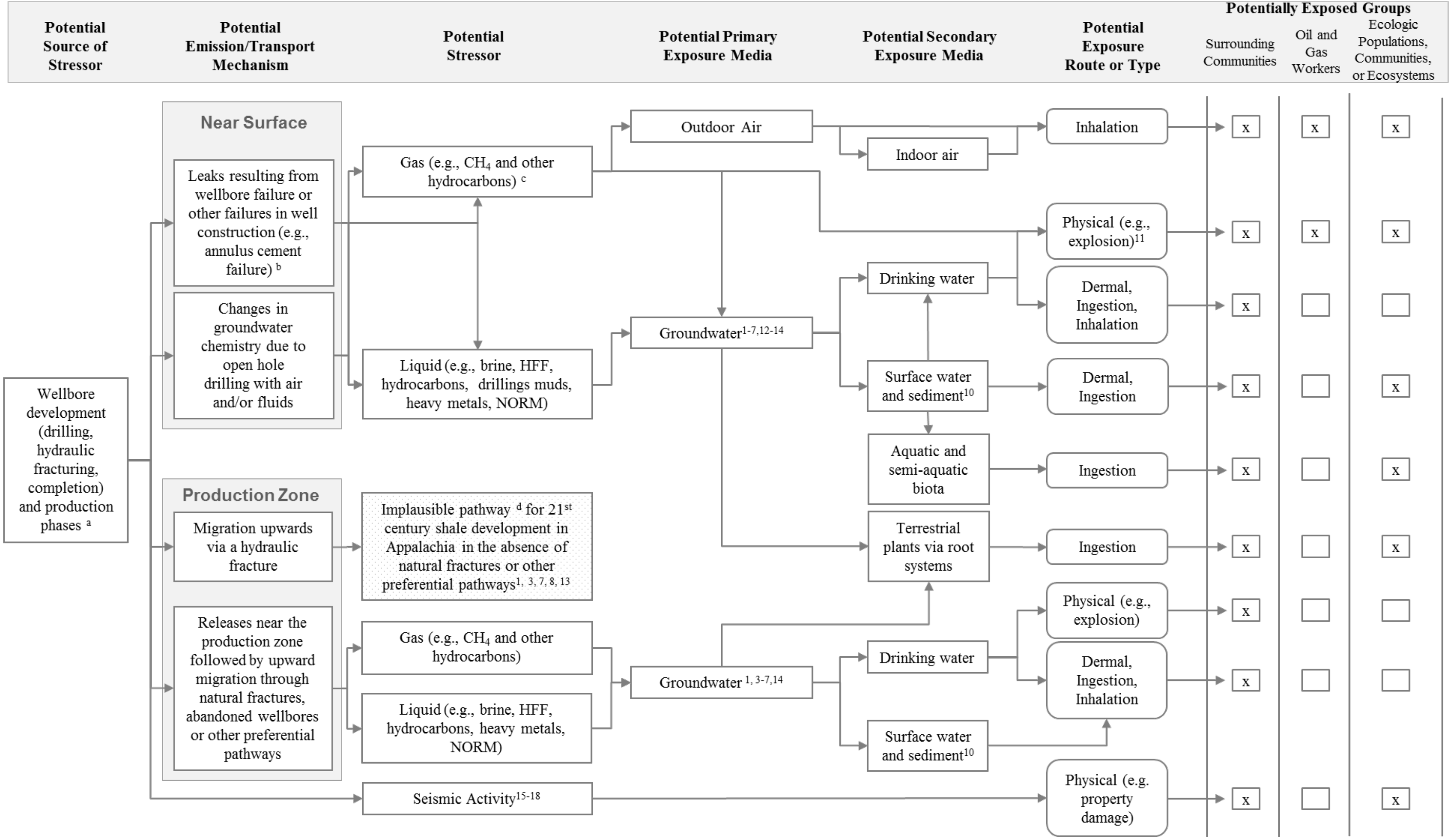
[3] Brine is water in the pore spaces of rocks thousands of feet below the ground surface with concentrations of dissolved solids that make it more salty than seawater. Brine is brought to the surface during oil and gas development.

Figure C-4. Potential exposure pathways related to the wellbore. All pathways considered by the Committee are shown regardless of their likelihood or significance. Superscripted numbers indicate a reference that can be found at the end of this Appendix.



[a] Closed wells after production ceases might also be subject to the potential exposures shown in this figure.

[b] A wellbore failure is defined as any instance where gas or fluid unintentionally escapes from or enters the wellbore.

[c] Gas entering aquifers with potable water could originate from various sources, including shallow (non-target) gas-bearing formations or the targeted formations.

[d] This pathway is implausible for shale resources currently being developed in the Appalachian basin (e.g., Marcellus and Utica) in the absence of natural fractures or other preferential pathways that can connect fractures created with high-volume hydraulic fracturing with freshwater aquifers that are thousands of feet above them..

x Potential exposure

PPE Personal protective equipment

HFF= Hydraulic fracturing fluids
VOCs= Volatile organic compounds
NORM= Naturally occurring radioactive material
CH_4= Methane

Composition and toxicity of hydraulic fracturing fluids. Before well stimulation, about 1 to 10 million gallons of water per well are typically mixed with chemicals and proppant to form hydraulic fracturing fluids. Fracturing fluid composition varies and has been reported based on a review of publicly available data (Gallegos and Varela 2015; EPA 2015; Stringfellow et al. 2014). Some chemicals in fracturing fluids can have carcinogenic, endocrine-disrupting, and other toxic properties (Kassotis et al. 2015; 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 exposures. For many compounds used in hydraulic fracturing fluids, there is inadequate toxicologic information (EPA 2015), and some compounds are not publicly known because they are regarded as confidential business information. There are active efforts to develop fracturing fluids that are environmentally benign (e.g., American Chemical Society Green Chemistry Institute Hydraulic Fracturing Roundtable).

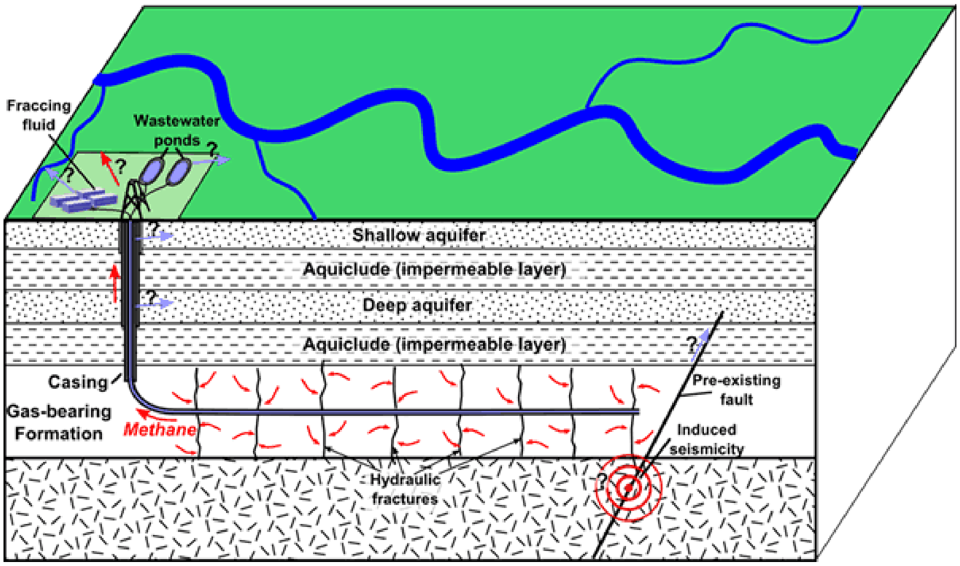


Figure C-5. Possible fluid migration pathways and other environmental concerns associated with hydraulic fracturing. Potential exposures discussed in this Section (C.1) include migration of CH_4 across wellbores into deep or shallow aquifers, migration of CH_4 up an inadequately cemented wellbore, and induced seismicity stimulated by hydraulic fracturing treatments. Potential migration of CH_4 into aquifers along natural pathways is not depicted in this figure. This figure does not include potential pathways related to the transport of fluids by truck or pipeline; those pathways are considered in Section C.1.5 (Source: Mike Norton, Wikimedia Commons.)

Vertical migration from the production zone. After fracturing fluids are mixed, they are injected at high pressure into the subsurface in a series of stages that causes microfractures in the target formation near the horizontal wellbore. There is general consensus that gases and liquids at production depth for tight oil and natural gas formations cannot migrate upward by way of fractures created by hydraulic fracturing (EPA 2015; Llewellyn et al. 2015; Jackson et al. 2014; Flewelling and Sharma 2013; Sharma et al. 2015; Soeder et al. 2014). An exception is where a pre-existing preferential pathway exists, such as an abandoned well, and pressure conditions are conducive to upward migration. In the absence of preferential pathways, upward migration is limited by a number of factors, such as layers of rock with lower permeability above the oil- or gas-containing formation; thousands of feet separating the highest induced fracture from the deepest aquifer; and elevated pressures during hydraulic fracturing being too brief to mobilize gases and liquids thousands of feet through some impermeable rock formations. The situation is different with coalbed methane development, which targets formations that are closer to the surface and that can be in or near freshwater aquifers.

Hydraulic fracturing and induced seismicity. Hydraulic fracturing has been suggested as a cause of induced seismic events (Figure C-5). Few incidents of “felt seismic activity” (generally of Richter magnitude [M] ≥ 3.0; National Research Council 2013) in North America (Oklahoma, Ohio, and British Columbia) have been potentially linked to the hydraulic fracturing process (Skoumal et al. 2015; Farahbod et al. 2015; Friberg et al. 2014; Holland 2013). As reported by multiple reviews, hydraulic fracturing has been responsible for earthquakes of small magnitude ($M \leq 2.0$, referred to as microseismic events) that have not caused damage (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 a wastewater disposal technique, commonly referred to as “deep-well injection,” in underground injection control wells. See Section C.1.5 for more details.

Waste spills. Water and other residual debris flow back from the well for 1 to 2 weeks after hydraulic fracturing. The general composition of flowback water is a mixture of hydraulic fracturing fluid and natural formation fluid; the latter makes up a greater percentage of the mixture over time (Ziemkiewicz and He 2015). On-site mixing and storage of wastewater and fracturing fluids, including the chemicals mixed to create these fluids, makes spills and subsequent contamination of soil, groundwater, surface water, and sediment possible. Brantley et al. (2014) described incidents in Pennsylvania where fracturing chemicals, drilling fluids, flowback water, and sediment were released to soil and surface water as a result of blowouts, trucking accidents, and leaks in pipes, valves, and storage tanks. An analysis by Rahm et al. (2015) of data from the Pennsylvania Department of Environmental Protection (PA DEP) suggested that spills were the most frequently reported type of environmental violation for OGD operators in the state. These spills could be contained on site and recovered, flow directly to surface water, or infiltrate from the land surface to surface water and groundwater through permeable soils, weathered bedrock, improperly constructed wellbores, or other routes (EPA 2015; Veil 2015). Evidence from Colorado suggests that spills or waste impoundment leaks have led to groundwater contamination with benzene, toluene, ethylbenzene, and xylene (BTEX; Gross et al. 2013). Changes in stream water quality resulting from a discharge of fracturing fluid have been associated with exposures in fish species in one study (Papoulias and Velasco 2013b). On the other hand, synoptic baseflow sampling of streams from an area of accelerating shale gas development in Appalachia showed no correlation between geochemical characteristics of stream water and the different categories of Marcellus Shale production (Pelak and Sharma 2014).

Naturally occurring radioactive material (NORM). Low-level ionizing radiation and heavy metals are known to be present both in flowback water and especially in solid waste materials, such as drill cuttings and sludge (Phan et al. 2015). Total beta radiation activity and lead concentrations in drill cuttings can substantially exceed regulatory guidelines for handling wastes from conventional wells (Johnson and Graney 2015; Rich and Crosby 2013), suggesting a potential exposure hazard for workers involved in the storage and transport of solid wastes from OGD (see below for further discussion of waste management).

Sensory stressors. Noise and light production continues after site preparation, occurring 24 hours a day, 7 days a week, during the drilling and hydraulic fracturing phases. Flaring is another source of noise, along with on-pad truck traffic, diesel and natural gas engines powering generators, shale shakers, drill rigs, pumps required for hydraulic fracturing, and other machinery. Measurements and estimates of noise at fenceline distances from OGD sites during the development phase have suggested that operations can exceed levels at which noise becomes an annoyance or interferes with daily activities (McCawley 2013; NYSDEC 2015). The highest noise levels are expected during hydraulic fracturing (NYSDEC 2015). For workers, exposure depends on not only the level of noise but on the use of personal protective equipment. Artificial lighting from operations can intrude into homes and may be especially intense during flaring operations (NYSDEC 2015). Malodorous compounds, such as H_2S and some VOCs, can be emitted during the development phase (Pennsylvania Department of Environmental Protection 2010; New York State Department of Health 2014; McCawley 2013).

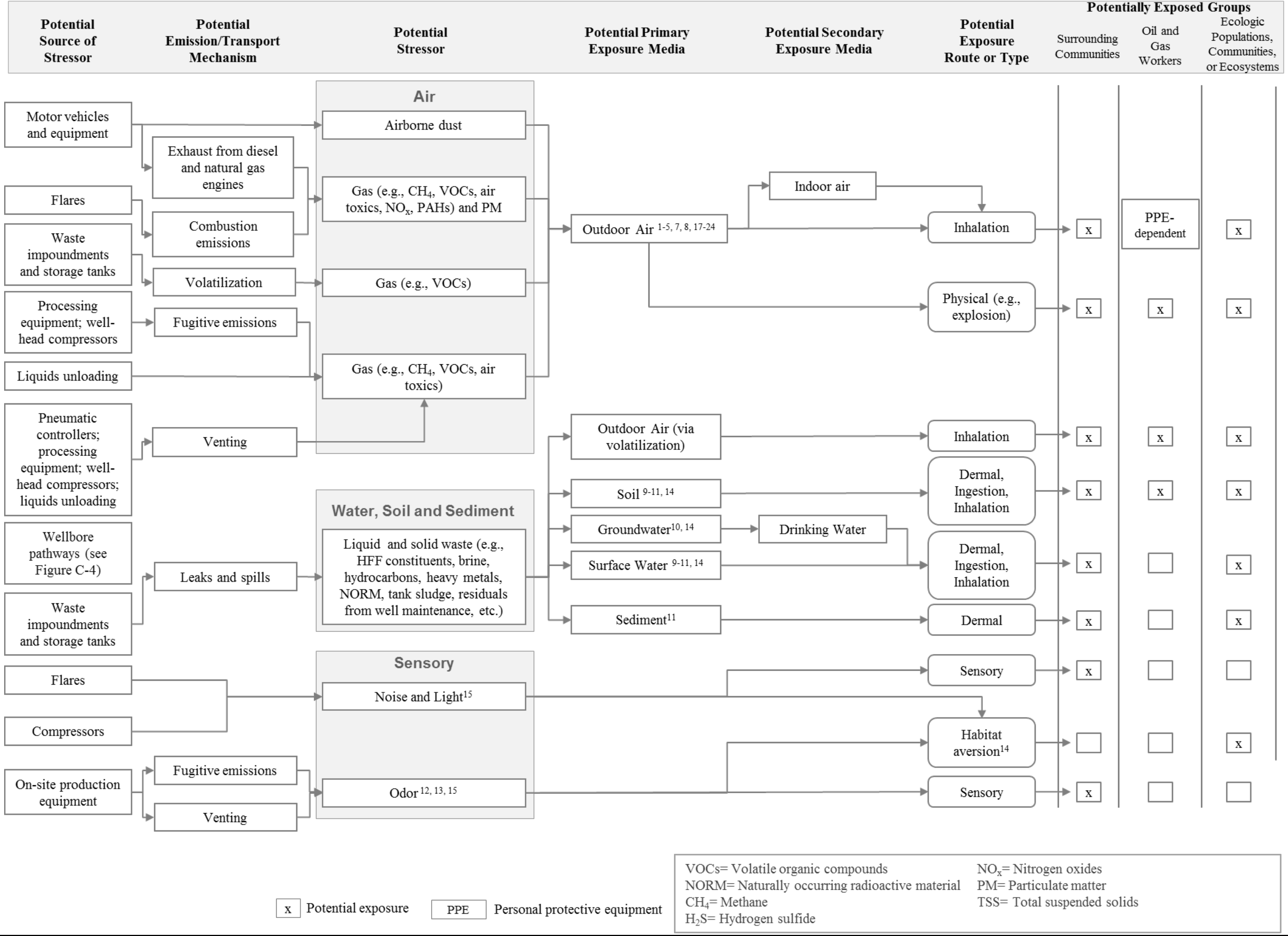
C.1.4 Production

Figure C-6 summarizes exposures that might arise at the well pad during the production phase.

Composition and management of produced water. During this phase, produced water is returned to the surface in amounts that diminish over time. Produced water is composed primarily of brine, but can also contain hydrocarbons, heavy metals, and NORM in various concentrations depending on the target geologic formation (Ziemkiewicz and He 2015; Akob et al. 2015; Capo et al. 2014; Engle and Rowan 2013; Rowan et al. 2011; Rowan et al. 2015). The highest NORM concentrations in U.S. shale plays, for example, are generally found in the Marcellus Shale.

The amount of produced water also depends on the well’s connection to deep, water-bearing zones in or near the oil or gas source rock. Wastewater can be stored in aboveground impoundments or on-site storage tanks; the latter have become more prevalent in Appalachia in recent years. As noted above in the section on development-related exposures, on-site storage of waste products creates the potential for spills or leaks. Produced water and other wastes, such as flowback water and drilling fluids, may also be treated or recycled for use on site. This practice has been increasing in states like Pennsylvania since the late 2000s (Rodriguez and Soeder 2015; Veil 2015). Potential exposure pathways related to the treatment and disposal of wastewater are shown in Figure C-7.

Figure C-6. Potential exposure pathways related to operations on the well pad during the production phase. All pathways considered by the Committee are shown regardless of their likelihood or significance. Superscripted numbers indicate a reference that can be found at the end of this Appendix.



Wellbore integrity. As noted in Section C.1.3, oil and natural gas wellbores have been known to fail as a result of poor engineering practice or exposure to deleterious chemical or physical conditions over time. Failed wellbores can potentially affect air or water resources by acting as pathways for the migration of gases or liquids.

Air emissions. Pneumatic controllers, venting, and on-site fugitive emissions from pipes, storage tanks, dehydrators, liquids unloading (i.e., the periodic removal of accumulated liquids from the wellbore to maintain gas production), and gas-processing equipment can emit CH_4, VOCs, air toxics, and potentially H_2S (Table C-2; Allen et al. 2015; EPA 2014a; 2014b; 2014c; 2014d; 2014e). There can also be combustion associated emissions (NO_x, PM, and VOCs) from a well pad during production but these are much less common than fugitive and venting emissions. They include occasional flaring operations and natural gas engines that power wellhead compressors. Wellhead compressors are rare in the Appalachian Basin today. Flares are used to control emissions of CH_4 and associated VOCs. They typically greatly reduce, but do not eliminate these emissions. All of these emissions have the potential to impact air quality.

Table C-2. Principal air emission sources during the production phase of an OGD well pad.

Source Category	NO_x	VOCs	PM	Air Toxics	Climate Forcers[a]
Natural gas engines and turbines used to drive compressors	●	●	●	●	●
Vents at compressor stations, well sites, etc.		●		●	●
Fugitives associated with liquid unloading, pressurized equipment, etc.		●		●	●
Processing and treatment equipment such as heaters, dehydrators, and separators	●	●	●	●	●
Blowdown venting		●		●	●
Storage tanks		●		●	●
Gas-driving pneumatics		●		●	●
Flares	●	●	●	●	●

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

Regional studies (Pekney et al. 2014; Roy et al. 2014; Swarthout et al. 2015) have suggested that Appalachian air quality (e.g., ozone and $PM_{2.5}$) may be affected by production-related emissions of ozone precursor gases (NO_x and VOCs) and $PM_{2.5}$. Except for important work on CH_4 emissions (Allen et al. 2015; Mitchell et al. 2015; Peischl et al. 2015; Pétron et al. 2014; Swarthout et al. 2015; Zavala-Araiza et al. 2015), few studies have reported chemical concentration data for air quality that corresponded to specific operations and processes on the well pad during the production phase.

Sensory stressors. Light, noise, and odor can continue on the well pad during the production phase. Flaring operations, though not as common during production as development, produce noise and artificial light. Compressors can produce around-the-clock noise that in some instances has exceeded state maximum allowable noise limits at fenceline distances (Maryland Institute for Applied Environmental Health 2014). Studies to date have only measured or estimated noise at various setback distances; they have not directly measured human or ecological exposures (NYSDEC 2015). Similarly, odor-producing compounds (e.g., H_2S) have been measured near well pads during the production phase (Pennsylvania Department of Environmental Protection 2010; Eapi et al. 2014).

C.1.5 Beyond the Well Pad

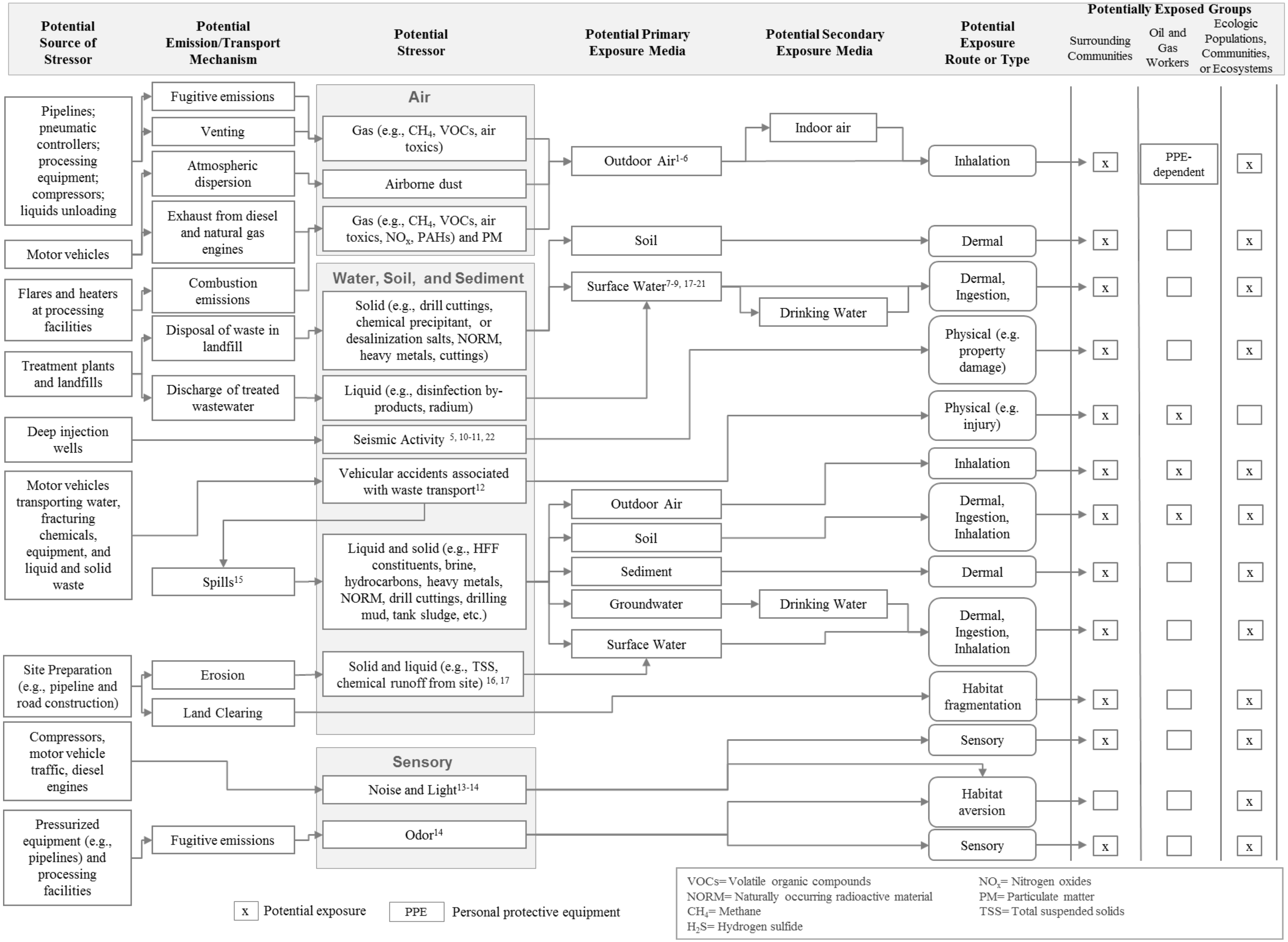
Oil and natural gas activities extend beyond the well pad during both development and production phases, and some activities continue beyond the production phase of any individual well (e.g., at gathering facilities, processing plants, and compressor stations). Potential exposure pathways related to these activities are summarized in Figure C-7.

Landscape change. Landscape changes that result from the creation of off-pad infrastructure (e.g., roads, pipelines, and processing facilities) can lead to erosion, sedimentation, and habitat fragmentation. Erosion-related violations and potential exposures are discussed in Section C.1.2. Johnson (2014) projected that pipeline construction could be responsible for 70% of oil and natural gas-related conversion of core forest habitat to edge habitat in Pennsylvania by 2030. The potential impacts of habitat fragmentation are summarized in Section C.2.

Air emissions. Midstream facilities and equipment are important sources of air emissions during the production phase. They include gathering pipelines and the equipment at gathering facilities: compressors (driven by electric motors and/or natural gas–fired internal combustion engines or turbines), dehydration systems to remove water, and treatment systems to remove H_2S or carbon dioxide. Processing plants often house this equipment on a larger scale, acting as central nodes in a system of smaller gathering facilities. Processing plants also separate natural gas liquids (such as ethane, propane, butane, and heavier hydrocarbons) from CH_4. Natural gas engines and turbines emit a mixture of CH_4, VOCs, air toxics, NO_x, PM, and climate forcers (see Figure C-2). Pressurized equipment that exists along gathering pipeline networks, such as pneumatic controllers and the pipelines themselves, can emit CH_4, VOCs, and air toxics through vents or leaks (Table C-2; Allen et al. 2015; Mitchell et al. 2015; Subramanian et al. 2015; EPA 2014a; 2014c; 2014e). Although fewer in number than well pads, midstream facilities such as processing plants and compressor stations service multiple wells and are often larger than well pads. These facilities have substantially more equipment and more emissions (Mitchell et al. 2015; Subramanian et al. 2015).

Transport-related spills. Increased rates of motor vehicle accidents in Pennsylvania have been attributed to OGD (Muehlenbachs and Krupnick 2013; Graham et al. 2015). Because a number of these vehicles are trucks transporting drilling and fracturing chemicals to well sites and wastewater to treatment and disposal facilities, a trucking accident could result in a spill to soil, surface water, and other environmental media.

Figure C-7. Potential exposure pathways related to operations beyond the well pad. All pathways considered by the Committee are shown regardless of their likelihood or significance. Superscripted numbers indicate a reference that can be found at the end of this Appendix.



VOCs= Volatile organic compounds
NORM= Naturally occurring radioactive material
CH_4= Methane
H_2S= Hydrogen sulfide
NO_x= Nitrogen oxides
PM= Particulate matter
TSS= Total suspended solids

Water use. Water scarcity is much less of an issue in the Appalachian region than in the western and southwestern regions of the United States, but fracturing operations can stress specific water bodies if water withdrawals are not overseen adequately. Rahm and Riha (2012), for example, report an analysis that indicates that restrictions on withdrawals from small streams are needed to maintain minimum low flow under severe conditions. The impact of decreased water quantity on aquatic ecosystems is discussed in Section C.2.

Waste management. A number of options have been used to manage wastewater (i.e., primarily produced water) from OGD, such as treatment and discharge, underground injection, and recycling. Figure C-8 shows how produced water was managed in the United States in 2007 and 2012, and in the three Appalachian states with the highest rates of OGD in 2012. Nationally, injection of produced water to enhance recovery in conventional oil fields has dominated. But this use is far less prevalent in the Appalachian states, where underground injection, transport off-site for commercial treatment and disposal, and beneficial reuse (e.g., recycling for use at the well pad and, to a limited extent, road de-icing) have been most common.

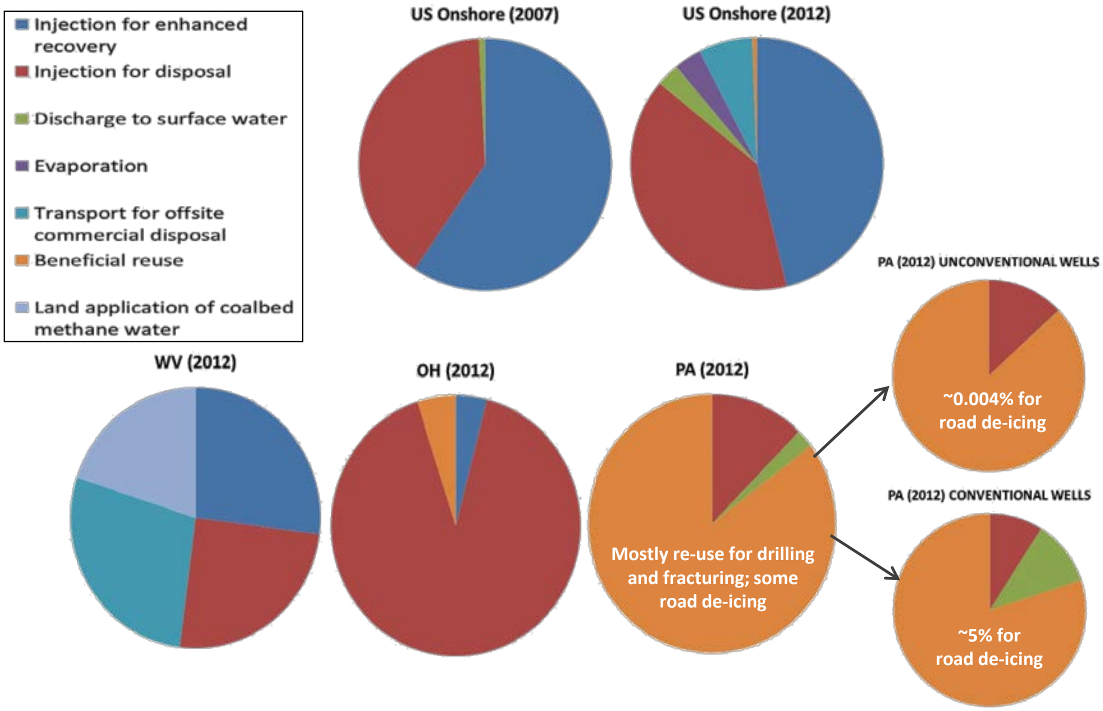


Figure C-8. Management of produced water from conventional and unconventional wells. The figure was created using data reported in “U.S. Produced Water Volumes and Management Practices” in 2012. Prepared for the Ground Water Protection Council by Veil Environmental, LLC. April 2015.

In the early days of Marcellus development in the Appalachian region, operators often sent wastewater to publicly owned treatment works and other municipal treatment facilities that had not been designed to handle the wastewater’s high concentrations of salt and naturally occurring radioactive material (Vidic et al. 2014). Studies from the Appalachian region have suggested that increased levels of radium and barium in sediments and streams, respectively, were related to discharges of treated wastewater during this timeframe (Warner et al. 2013; Ferrar et al. 2013b). Bromide, a product of incompletely treated wastewater, can react with chlorine during water treatment to form carcinogenic trihalomethanes. Elevated levels of bromide were detected in

Pennsylvania surface water downstream of the discharge points of publicly owned treatment works (Wilson and VanBriesen 2012; Wilson et al. 2014). State regulations and requests by the PA DEP addressed the use of publicly owned treatment works to treat Marcellus-related wastewater. Work continues on the investigation of surface water quality in the region (Rodriguez and Soeder 2015; Vidic et al. 2014; Parker et al. 2014; Hladik et al. 2014).

Industrial treatment facilities are also used to treat OGD wastewater. The Center for Sustainable Shale Development, a collaboration of environmental organizations and energy companies encouraging responsible shale gas development in the Appalachian region, recently expanded its standard for wastewater to include not only recycling and underground injection but also discharge through regulated centralized waste treatment facilities. These specialized facilities are designed to handle waste with high salinity and, in some cases, radioactive materials such as radium. Water treated at centralized waste treatment facilities is often discharged to surface water or publicly owned treatment works, reused for hydraulic fracturing, or reused for other purposes (EPA 2015; Rodriguez and Soeder 2015; Vidic et al. 2014).

An additional off-site waste management option is to dispose of wastewater in underground injection control wells. This option is common in Ohio, where a number of underground injection control wells are currently operating. However, it has not been economically viable for many operators in Pennsylvania and West Virginia, where the limited number of injection wells forces operators to transport waste over long distances (Vidic et al. 2014). Deep-well injection is a known source of induced seismic activity (National Research Council 2013; Andrews and Holland 2015; Hornbach et al. 2015; Ellsworth 2013). In areas such as Ohio, Oklahoma, and Kansas, moderate earthquakes have been associated with deep-injection wells receiving wastewater from oil and natural gas development. The number of earthquakes of > 3.0 magnitude has increased significantly in these areas, including a limited number of physically damaging earthquakes of > 5.0 magnitude (McGarr et al. 2015).

Solid wastes are often disposed of at nearby sanitary landfills. Exposures to radiation and other potential health stressors in the waste could arise if spills along roadways have not been managed properly or if wastes have not been handled properly at the landfill.

Sensory stressors. Truck traffic can be a source of noise and light. The Maryland Institute for Applied Environmental Health (2014) measured noise from off-site compressors in West Virginia and detected levels that exceed regulatory thresholds. Section C.2 describes the potential impacts of noise on ecosystems; however, no studies were found linking oil and natural gas activities to excessive noise exposures in ecologic populations. As with on-site production equipment, components of the natural gas gathering system (e.g., compressor engines, pipelines, and pneumatic controllers) could potentially emit malodorous VOCs and H_2S, particularly when not operating as intended.

C.1.6 Closure and Post-Production

Wellbore integrity. A well can be hydraulically fractured once or multiple times before it is deemed unproductive. At this point, the well must be properly sealed (plugged) by the operator to prevent petroleum, brine, or natural gas from escaping to the environment. This is accomplished using multiple cement plugs in the wellbore. As noted in Section C.1.3, oil and natural gas wellbores are known to fail as a result of exposure to deleterious chemical or physical conditions over time. Many improperly plugged abandoned wells in the region (see Davies et al. 2014) from earlier conventional development can potentially affect air or water resources by acting as pathways for the migration of gases or liquids when pressure conditions are conducive to upward migration (Kang et al. 2015; Kang et al. 2014). State programs (e.g., in Pennsylvania and Texas) that target and plug abandoned wells are currently in place, though the location and depth of many such wells is currently unknown (Davies et al. 2014). This discussion reflects experience with closure and regulation of earlier wells. The peer-reviewed literature does not include similar studies involving only newer OGD wells.

Landscape change. Once a well is closed, operators are typically required by state regulations to reclaim the well pad to original or near-original landscape conditions, including vegetation, contour, and drainage. As noted in Section C.1.1, oil and natural gas activities can also affect dynamic soil properties. It is unknown how long soil and other landscape conditions remain affected after OGD sites are reclaimed (Fink and Drohan 2015).

C.2 POTENTIAL IMPACTS ON ECOLOGICAL HEALTH

This section explains how the exposures described in Section C.1 might affect aquatic and terrestrial ecosystems.

C.2.1 Aquatic Ecosystems

Impacts related to changes in water availability. As noted in Section C.1, the hydraulic fracturing process requires about 1 to 10 million gallons per well. This water can come from various sources, such as recycled wastewater or nearby streams (see Section C.1.4). Withdrawal of water from surface water and freshwater aquifers is typically not an issue in the Appalachian region and amounts to only a fraction of the region’s industrial water use. In certain circumstances, however, OGD water usage might affect the structure and function of aquatic ecosystems. Water withdrawals from low flow or drought-condition streams can decrease or degrade 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 types 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 hydraulic fracturing in Pennsylvania (Shank 2013).

Impacts related to changes in water quality (including sedimentation). A variety of processes associated with OGD can lead to changes in water quality. Although produced water is often treated for discharge or recycling, or injected for disposal, it can sometimes be released intentionally and accidentally (see Section C.1). Laboratory studies of three native Pennsylvania mayflies and other model species found that produced water from OGD operations in the Marcellus formation was acutely and chronically toxic and that multiple dilutions were required to decrease toxicity (Stroud Water Research Center 2013). Changes in stream conditions (e.g., pH and conductivity) from the discharge of oil and natural gas wastewater have led to lethal and nonlethal responses in fish (Papoulias and Velasco 2013a). Grant et al. (2015) observed decreases in fish biodiversity and macroinvertebrate taxa richness as well as changes in stream conditions (higher dissolved mercury, lower pH, and higher dissolved organic matter) in watersheds affected by OGD. In Arkansas streams associated with the Fayetteville shale play, Austin et al. (2015) observed increases in chlorophyll a and a correlation between gross primary productivity and OGD. Across these same sites, Johnson et al. (2015) observed that macroinvertebrate species richness and abundance correlated positively with these same conditions, presumably reflecting the increase in algal availability.

Few studies have directly addressed the relationship between oil and natural gas–related activities and erosion and sedimentation (Williams et al. 2008; McBroom et al. 2012). Increased sediment concentrations in Appalachian streams can 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.

C.2.2 Terrestrial Ecosystems

Habitat change, loss, or fragmentation. Well pads and other oil and natural gas facilities and infrastructure (e.g., compressor stations, processing facilities, roads, and pipelines) contribute to the creation of new patterns of land use and the introduction of multiple stressors, such as noise, light, and chemicals, from normal operations and under accidental conditions. These stressors can lead to habitat fragmentation,[4] habitat loss,[5] and other habitat changes. The ecological impacts of habitat loss and fragmentation range from changes in community structure and composition to direct mortality (see below).

A report on the Marcellus region predicted that between 700,000 and 1,750,000 acres of Appalachian forest habitat might be converted to oil and natural gas infrastructure or to edge habitat resulting from such development by 2030, with most of the conversion (70%) resulting from pipeline construction (Johnson 2014). As a result, regions that were once dominated by deep-forest habitats may become fragmented or dominated by edge habitats. These alterations would lead to changes in light, temperature, moisture, and other features that can directly and indirectly affect surrounding ecosystems (Allred et al. 2015; Brittingham et al. 2014; Drohan et al. 2012).

Biotic impacts resulting from habitat loss related to OGD include decreases in secure habitat, disrupted breeding, and changes in community density and structure (Souther et al. 2014). A recent study of conventional oil and natural gas development (Thomas et al. 2014) suggested that these impacts increased with increases in development. Habitat fragmentation is well studied in general development scenarios (Souther et al. 2014; Holderegger and Di Giulio 2010; Gibbs 1998; Small and Hunter 1988; Trombulak and Frissell 2000) and has been associated with changes in wildlife behavior, reduced reproduction success, and the introduction of invasive and competitive species (Brittingham et al. 2014).

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[4] Breaking up a contiguous area of habitat as a result of land uses such as roads, pipelines, and other pathways.

[5] Direct loss of habitat caused by the footprint of well pads and other infrastructure.

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 ecological 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 habitats near compressor stations used in oil and natural gas development (Bayne et al. 2008; Francis et al. 2011). Similar studies of the Marcellus region are forthcoming (PA DCNR 2014).

Change in competitive interactions and introduction of invasive species. Heavy equipment and traffic related to OGD can introduce invasive species to Appalachian habitats. The Pennsylvania Department of Conservation and Natural Resources (2014) assessed non-native invasive plant species at 18 representative well pads across core forest districts and found 11 species of invasive plants; 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; conventional oil and natural gas development-related) and can change forest vegetation trajectories (Horsley et al. 2003).

Toxicity and direct mortality. Multiple studies have suggested that air emissions from conventional oil and natural gas operations may be linked to health impacts on domestic animals (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). In addition, Pekney et al. (2014) detected air pollution from conventional oil and natural gas operations in heavily forested rural air-sheds in the Marcellus region (Pekney et al. 2014). Drohan and colleagues estimated that 45% to 62% of Marcellus well pads in Pennsylvania were placed on agricultural land, but no studies of OGD impacts on domestic livestock were found for the region. For some air pollutants associated with OGD emissions, such as ozone, ecological effects are well documented and plant indicator species are well known (Fredericksen et al. 1996). In many cases, however, the responses of flora and fauna to air pollution in rural settings are not well understood.

Conventional oil and natural gas wastewater (flowback and produced water) has been linked with short-term plant mortality and increased concentrations of brine in soil when spilled or spread in forested land (Adams 2011; Dewalle and Galeone 1990; Auchmoody and Walters 1988). The current chemical composition of wastewater from OGD might differ from the composition at the time these reports were published. Nonetheless, reports based on prior conditions are relevant for understanding past short-term and potentially long-term impacts.

Impacts on threatened and endangered species habitats. In addition to potential impacts on important and rare habitats, OGD 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 reduced in size and 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 change, or behavioral change in these species as a result of OGD. However, the PA DCNR (2014) is sponsoring a study of the impact of well development on timber rattlesnakes (*Crotalus horridus*), a species of conservation concern.

In addition to these species, habitats and very specific geographic areas have been designated by states and environmental organizations as being of high conservation concern. These include the Audubon Society’s Important Bird Areas (*http://web4.audubon.org/bird/iba/*) and the Commonwealth of Pennsylvania’s Exceptional Value and High Quality waters. One projection estimated that about 3,500 OGD well pads could be located within 0.5 miles of High Quality or Exceptional Value waters (Johnson et al. 2010).

C.2.3 Cumulative Ecological Effects

Ecotoxicology in natural systems is complicated by the suspected importance of cumulative effects of stressors encountered individually at subtoxic levels. OGD-related stressors might act individually or cumulatively to disrupt biodiversity or ecosystem services. Souther et al. (2014) discussed gaps in the understanding of potential cumulative impacts of OGD on ecological health. A limited number of studies have examined the relationship between cumulative exposures to OGD and ecological impacts. Changes in land-use patterns have been associated with negative responses in macroinvertebrate communities (Burton et al. 2014). Increased density of gas wells has been linked to increased fish (red fin darter) mortality in non-Appalachian settings (Stearman et al. 2015). 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.

C.3 POTENTIAL IMPACTS ON HUMAN HEALTH

This section briefly discusses how the exposures described in Section C.1 might affect the health of oil and natural gas workers and people living in communities near OGD operations. 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 stressors (e.g., PM), sensory stressors (e.g., odor and light), physical agents (e.g., radiation and silica), and physical hazards (e.g., traffic accidents) associated with OGD, as described in Section C.1. The recent increase in OGD has led to scientific interest in the potential impacts on human health, yet few exposure or health studies have evaluated the actual types and levels of exposure related to OGD and whether they might lead to health effects (Adgate et al. 2014; Goldstein et al. 2014).

The potential for human health effects of OGD has been the subject of several reviews in the United States (e.g., Maryland Institute for Applied Environmental Health 2014, Penning et al. 2014, Adgate et al. 2014, National Research Council 2014, and EPA 2015) and around the world (e.g., Public Health England et al. 2013). Except for Esswein et al (2013; 2014), most of these reviews focused on the health of people living near oil and natural gas operations.

There have been few, broad population-based epidemiologic studies that directly addressed the physical or mental health effects of OGD — particularly in the Appalachian region. Most studies have involved community-engaged research (which measures community perceptions of risk, self-reported symptoms, and other anecdotal information) or research based on ecological or correlational designs (Rabinowitz and Slizovskiy 2014; Steinzor et al. 2012; 2013; Saberi et al. 2014; Perry 2013; Southwest Pennsylvania Environmental Health Project [SWPA EHP] 2013; Ferrar et al. 2013a).

There is variability in the populations exposed and the type and degree of exposure. Occupational exposure to chemical, physical, and psychological stressors can happen on the well pad and during any phase of development and production. Community members may be exposed by way of air, water, or other environmental 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 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 OGD 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 and Goldstein et al. 2014). But at this time, insufficient data are available in most instances to quantify exposures to multiple stressors or to predict health effects from these exposures. These problems are exacerbated in the case of OGD by the lack of chemical-mixture toxicity data and the fact that few studies have used reliable worker and community exposure data collected at locations and over periods relevant to understanding potential risks to health.

A great deal of OGD is occurring in sparsely populated areas, limiting the possible sample size and statistical power of epidemiologic 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., the Barnett Shale near Dallas–Fort Worth), making it difficult to parse the contributions of other pollution sources. Additionally, exposure metrics have not been well defined. Oil and natural 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.

C.3.1 Oil and Natural Gas Workers

The industry and regulators have protocols to protect workers. Nevertheless, workers can be exposed to a range of health stressors, although the degree of exposure is strongly dependent on recommendations for and use of appropriate personal protective equipment.

Chemical stressors and physical agents. Many community concerns about oil and natural gas operations focus on chemical exposures. Oil and natural gas workers actively use these chemicals or work in proximity to them, and consequently face the potential for higher exposures than other 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 OGD workers, and the rapid pace of changing technology makes occupational studies challenging to conduct and interpret. Areas of particular safety concern include increased traffic; use of substantial volumes of liquids at high operational pressures; exposure to chemicals used in fracturing fluid, flowback water, and produced water; and the need for intermittent work in hazardous operations.

A unique concern for OGD workers, as distinct from workers in the rest of the oil and natural 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 as it is transported to the well site from storage and especially during mixing or blending into the fracturing fluid. As discussed in Section C.2, exposure studies have identified crystalline silica as a respirable hazard for workers. Respiratory exposure to crystalline silica can cause silicosis (a fibrotic lung disease), and it can increase the risk of autoimmune disorders, susceptibility to infections (such as tuberculosis), kidney disease, and lung cancer (Esswein et al. 2013). For silicosis and other silica-related diseases, there can be a substantial latency between the initial exposure and the onset of detectable disease processes, meaning it will take time and effort to understand the risk to workers. NIOSH and others are developing hazard-reduction engineering and process protections that could reduce workplace exposures and prevent health risks (such as silicosis) if used appropriately.

Workers may be exposed to benzene and other VOCs at the wellhead of any oil and natural gas operation; this exposure is not unique to OGD. In OGD, benzene can also accompany the production of CH_4 or arrive along with substantial quantities of initial flowback water (Esswein et al. 2014). As discussed in Section C.1.3, VOC inhalation has been identified as a hazard for workers during the completion phase.

Diesel exhaust mixes with other sources of PM and other emissions, such as NO_x and carbon monoxide. These air pollutants have well-known health effects, including increased mortality from respiratory causes, cardiac causes, and all causes combined, as well as increased incidence of pulmonary conditions, such as asthma and respiratory infections, and of other ailments. Diesel exhaust from older engines has also been classified as a known human carcinogen by the International Agency for Research on Cancer (IARC). 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 equipped with after-treatment devices) are introduced into the on-road vehicle fleet. Rates of chronic obstructive pulmonary disease also increase with increased exposure to air pollution.

Low-level ionizing radiation is known to be present both in flowback water and especially in solid wastes, such as drill cuttings and sludge. The 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 of worker exposures or assessment of worker exposures associated with specific operations.

Physical hazards. Oil and natural 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 (Mason et al 2015b). 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 natural gas industry is about eight times greater than that of other occupations (Adgate et al. 2014; Retzer et al. 2013; Mason et al. 2015). OGD operations can thus be expected to feature a high rate of worker motor vehicle injuries and deaths (National Research Council 2014; Retzer et al. 2013). In contrast with these vehicular injury and fatality rates, however, the rate of nonfatal injuries is reported to be lower than in the construction industry (U.S. Bureau of Labor Statistics 2014).

Physical hazards are also associated with gases. Direct reading measures indicated that hydrocarbon vapors accompanying flowback fluids could 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 wells, with attendant consequences, including death.

Sensory stressors. Noise is well known to be a hazard in the oil and natural gas industry. Compressors have been measured at levels that can cause permanent hearing damage (Section C.1). Workers are usually closer to the source of noise than residential neighbors are, although worker exposure can be reduced with the use of personal protective equipment. In occupational settings (not oil and natural gas operations specifically), noise exposure has been linked with increased rates of myocardial infarction (Basner et al. 2014) and hypertension (Tomei et al. 2010).

Work schedules and shift work. Operations during some phases of OGD 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.

C.3.2 Communities living near OGD

Chemical stressors and physical agents. A few studies have characterized the emission and distribution of pollutants from the well pads and diesel traffic associated with OGD. For example, a recent study measured chemical concentrations in waste streams from OGD in the Marcellus formation to make inferences about exposures by way of water ingestion (Ziemkiewicz et al. 2014). McKenzie et al. (2012) used air quality data collected along the perimeter of well pads in Colorado to assess human exposure. Data from these and other recent studies, often measured as 24-hour-average concentrations, did not adequately characterize the intensity, frequency, or duration of actual human exposures. They also might not have captured the spatial or temporal variability in exposure within and across communities that is important for assessing risks to health (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 have distinguished OGD-related sources from other sources of the same chemicals (e.g., wood smoke, vehicle or farm machinery exhaust, or chemical applications on farms).

Some of the chemicals emitted during oil and natural gas operations (e.g., diesel exhaust and benzene) have well-known health effects (International Agency for Research on Cancer 2010; 2012; Duarte-Davidson et al. 2001) and thus have the potential to affect the health of nearby community members. A recent toxicological study by Kassotis et al. (2015) suggests that exposure to chemicals present in oil and natural gas-related fracturing fluids and wastewater can lead to adverse developmental and reproductive impacts in humans and animals under certain exposure conditions. Further, Yao et al. (2015) found that flowback water from OGD can induce the formation of malignant cells *in vitro*. However, well-conducted studies specifically linking exposures related to OGD, including fracturing fluids and flowback water, to adverse outcomes do not exist. Their absence is an important knowledge gap. In addition, little or no attention has been paid to the potential combined effects of exposures to complex mixtures of hazardous compounds (Goldstein et al. 2014).

OGD has been linked to adverse reproductive outcomes (McKenzie et al. 2014) and low birth weight (Stacy et al. 2015). 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 were mothers who lived in “low risk” locations. However, as the authors acknowledged, the study was subject to important sources of uncertainty, such as the exposure metric and proximity to wells, that were not specific to any particular health stressor. Stacy et al. (2015) reported lower birth weights associated with maternal proximity to unconventional gas drilling. The authors emphasized that the clinical significance of the birth weight differences they observed is not known. They also described use of proximity data as “a primitive surrogate for exposure.” Nevertheless, they concluded that their results underscored the need for larger studies with better measures of exposure. Given the limitations of these studies, it would not be appropriate to rely on them to reach definitive conclusions about adverse health outcomes related to OGD, but they should be considered when formulating hypotheses for future research.

Physical hazards. Increased industrial traffic in residential areas might also decrease access to outdoor recreational activities for residents who live near affected roads (Ortega et al. 2010). This effect is potentially important because of the known beneficial relationship between exercise and health. Rural areas of Appalachia often do not have infrastructure such as sidewalks or wide road shoulders (Figure C-12). Furthermore, increased traffic from drilling operations might increase the risk of traumatic vehicular 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 OGD activity (see Sections C.1 and C.4).

Figure C-12. A sign along a narrow, shoulderless road in West Virginia limiting truck traffic during school busing hours.

Sensory stressors. Residents of the Appalachian region have expressed concern about odor, noise, and light related to drilling, compressors, increased truck traffic, and hydraulic fracturing. Noise and bright light can affect sleep quality and cause sleep disturbances (Passchier-Vermeer and Passchier 2000). Studies in urban residential areas have suggested that increased traffic noise is linked to cardiovascular disease (Babisch 2011). Other potential health effects include stroke and hypertension (Basner et al. 2014). Artificial lighting can occur around the clock during some OGD phases. Light exposure can affect processes related to circadian rhythms, such as sleeping patterns and energy metabolism. Social changes associated with the growth and population influx caused by OGD also bring some predictable patterns of disease and injury (Adgate et al. 2014).

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). However, few studies have measured the prevalence of perceived stress in communities affected by OGD, and none have measured the relationship between health and clinically identified stress or stress biomarkers in such communities. The psychosocial effects of OGD as related to communities are discussed in Section C.4.

Self-reported health concerns. Several groups have conducted health surveys with people who live near OGD operations. Dermatologic, neurologic (including sensory and sleep), psychological or emotional, and respiratory symptoms were reported by survey respondents. 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 true random sampling) from several regions (Ferrar et al. 2013a; McDermott-Levy et al. 2013; Steinzor et al. 2013).

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

Less formal citizen surveys have suggested that odors might be a trigger for some symptoms, although systematic evidence is limited (Steinzor et al. 2012; Steinzor et al. 2013). OGD operations include a number of possible odor sources, such as diesel exhaust and VOCs. Holding ponds, which are less common in newer OGD operations but still present in some operations, might contain chemical mixtures that have their own odors and that can also be a nutrient source for microorganisms that can generate offensive odors (Akob et al. 2015; Cluff et al. 2014). A recent study from the Barnett Shale region in Texas found H_2S levels above odor detection thresholds at the operational fence line (Eapi et al. 2014).

Neuropsychological factors may also contribute to expressed symptoms and physical health outcomes. Ferrar et al. (2013a) reported that the belief that physical health had been affected was associated with reports of stress and loss of trust in industry representatives and government officials. This finding is consistent with previous research indicating that lack of trust can lead to amplified risk perception (Slovic 1987).

Whether any of the symptoms or diseases reported by people living near OGD operations were caused by these operations depends on the biological plausibility and degree of exposure. But exposure measurements are scant, and studies to date have been based on designs that limited the ability to draw firm conclusions. The principal utility of these health surveys, therefore, is in hypothesis generation for future health studies.

Epidemiological studies. Exposure assessments to evaluate health risks for people living near OGD 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 noncancer 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 various subcategories of wells (i.e., all gas wells, horizontal wells, horizontal gas wells, and Marcellus Shale wells). Although the methods used to quantify exposure differed among them, four 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 (Casey et al. 2015; Stacy et al. 2015; 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) and Stacy et al. (2015) described some of the limitations of their work; for example, residential proximity to, or distance from, oil and natural gas wells does not necessarily account for factors such as the phase of well development and production, the duration and severity of the exposures, the specific technology being used, other possible sources of the chemicals being monitored, or for meteorologic factors. Proximity may also reflect, in addition to chemical exposures, noise, light, and traffic, changes to community characteristics, and other factors that increase with proximity to the well site. Casey et al. (2015) improved on previous studies by assigning activity levels that were based, in part, on estimates of the duration of each phase of unconventional natural gas development (the types and duration of exposures likely differ among stages). Previous work assumed that exposures began on the spud date (i.e., onset of the drilling process) and continued indefinitely. However, these phase estimates are also subject to uncertainty and the study was limited, as with McKenzie et al. (2014) and Stacy et al. (2015), by the absence of direct, continuous measures of exposure. 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).

C.4 POTENTIAL IMPACTS ON INDIVIDUAL AND COMMUNITY WELL-BEING

This section summarizes how the exposures described in Section C.1 might affect the well-being of individuals and communities near OGD operations.

OGD can lead to a variety of positive outcomes for some individuals and some communities — including opportunities for new and higher-paying jobs, new income for some landowners who are able to lease their land for OGD activities, increased state revenue, and increased local business activity (see Table 1-1). At the same time social and psychosocial impacts can be expected to accompany OGD (Jacquet 2014). Such effects result in part from the scale and intensity of development activity in some locations and related changes in labor force demand, worker in-migration, local population change, and demands on infrastructure and services as well as a variety of other changes affecting the character of social and biophysical landscapes.

The high volume of truck and heavy equipment traffic required to support drilling and well completion operations appears frequently to result in concerns and problems with traffic flow and congestion, damage to roads and highways, increased accident rates, and reduced traffic safety (Brasier et al. 2011; Ladd 2013; 2014; Perry 2012; Schafft et al. 2014; Weigle 2011). Also, in the more rural and remote settings that experience extensive OGD activity a variety of effects associated with workforce in-migration and accompanying population growth pressures can be anticipated, at least during periods when drilling, well completion, and pipeline construction activities are most intensive (see Jacquet and Kay 2014). Areas experiencing OGD may experience substantial new demand for worker housing, leading to problems with housing shortages, increased reliance on temporary and in some cases substandard housing arrangements, rising costs for rental housing, and increased homelessness (Brasier et al. 2011; Perry 2012; Schafft et al. 2014; Williamson and Kolb 2011). Some of these impacts are interrelated with potential benefits in the form of increased regional property values as a result of increased housing demand (Muehlenbachs et al. 2013; Weber et al. 2014b).

Growth-induced demands on public facilities and infrastructure and on public as well as private-sector service providers can also be problematic, especially during development phases when a rapid increase in worker numbers can exceed the 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 [BBC] 2013; Brasier et al. 2011; Jacquet 2014; Maryland Institute for Applied Environmental Health 2014; Perry 2013; Theodori 2009; Weber et al. 2014a; 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, if taxation and revenue allocation structures fail to provide an adequate flow of funds to the affected communities (BBC 2013; Jacquet 2014; Jacquet and Kay 2014).

OGD can also place considerable strain on the social fabric of affected communities. Where development generates rapid growth effects there is 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 2013; Freudenburg 1986; Sampson 1991; Smith et al. 2001; Wynveen 2011). These changes may contribute to lowered interpersonal trust, manifested in part by increased fear of crime (BBC 2013; Brasier et al. 2011; Ladd 2013; Theodori 2009). Tensions and conflicts between “oldtimer” and “newcomer” populations may arise, exacerbating the erosion of trust among residents (BBC 2013; Brasier et al. 2011; Perry 2012; Wynveen 2011). In combination, such outcomes can contribute to a deterioration of the local social capital that is central to community well-being and adaptive capacity.

In addition to affecting the well-being of existing residents of communities experiencing OGD, these stressors can also have important effects on industry workers and their families who relocate to these areas. Insufficient infrastructure for housing, education, health care, and recreation can directly affect the quality of life for workers and their families. In addition, relocated workers and their families may be ostracized and scapegoated by other residents who view them as a source of rapid changes in community culture and of social divisions, distrust, and increased fear of crime. Because the OGD industry is not vertically integrated but instead relies on multiple layers of contract workers, there is typically not a single dominant employer with either the responsibility or capacity to address the needs of relocating workers and their families. With responsibility for planning and intervention widely distributed, the needs of relocating worker populations are likely to be largely unrecognized and unaddressed.

Tensions and conflicts among residents who hold divergent views about the consequences of resource development can also contribute to strained social relations (Gramling and Freudenburg 1992; Jacquet 2014; Ladd 2014; Perry 2012; 2013; Theodori 2009). Increased potential for wealth creation from OGD where resources are primarily privately owned can create highly varied outcomes with respect to how residents experience both “opportunities” and “threats” associated with OGD and to quite different views about the acceptability and desirability of resource development (Brasier et al. 2011; Perry 2012; 2013). Some residents are likely to experience significant economic benefits from leasing their land for OGD, 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 2013; Brasier et al. 2011). Also, 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 when concerns about potential environmental contamination from drilling and other OGD activities lead to widespread perceptions of risks to human health and safety and to distrust of individuals and organizations charged with protecting environmental quality and community health and welfare (Boudet et al. 2014; Brasier et al. 2011; Jacquet 2014; Kroll-Smith and Couch 1990; Ladd 2013; Perry 2012; Slovic et al. 1991; Stedman et al. 2012; Theodori et al. 2013). Perceived risks, reduced trust, decreased satisfaction, and disagreements about the nature and significance of environmental and community effects can lead in turn 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 1990; Ladd 2014; Perry 2012; Picou et al. 2004). Stigmatization of local residents and of entire local communities can occur as a result of characterization of the area by others as undesirable and potentially “contaminated” in terms of both environmental and social conditions (Edelstein 1988; Kroll-Smith and Couch 1990; Muehlenbachs et al. 2013; Perry 2013; Weigle 2011; Wulfhorst 2000).

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APPENDIX D: GLOSSARY

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

GLOSSARY

#

21st century oil and natural gas development (OGD) – The onshore development and production of oil and natural gas from unconventional resources in the Appalachian Basin as practiced today, recognizing that current industry practices continue to change in response to evolving technologies, regulations, and other factors.

A

Abandon – To cease producing oil or gas from a well when it becomes unprofitable. 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.

Air toxics – The Clean Air Act Amendments of 1990 specify a list of 187 hazardous air pollutants that are known or suspected to cause cancer or other serious health or environmental effects. These hazardous air pollutants are referred to throughout this report as air toxics. The list includes volatile organic compounds (VOCs), such as benzene and formaldehyde, as well as other pollutants, such as diesel particulate matter (PM).

Appalachian Basin – A geologic structure extending from Alabama northward to New York. Oil and natural gas have been extracted from this structure 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, near Titusville, Pennsylvania, in 1859.

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.

Barnett Shale – Hydrocarbon-producing geological formation consisting of sedimentary rocks and stretching from the Dallas–Fort Worth metroplex west and south, covering 5,000 square miles.

Blowout – An uncontrolled flow of gas, oil, or other well fluids from the well.

Brine – Water containing more dissolved inorganic salt than typical seawater.

C

Casing – Heavy steel pipe placed 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 freshwater aquifers.

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

Chemical stressor – A chemical agent (e.g., benzene) that might harm an organism, depending on the level of exposure.

Climate forcers – Gases or particles that alter the earth's energy balance by absorbing or reflecting solar radiation.

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 natural 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.

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.

Conventional oil and natural gas formation – A formation with relatively high permeability, in which the oil or natural gas has migrated to a natural reservoir and is held there by a rock unit that prevents further migration. When tapped, oil or gas from conventional formations flows readily into wellbores.

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

Cuttings – *See* Drill cuttings.

D

Deep-well injection – A technique in which wastewater, typically produced waters from the petroleum formation and flowback from the fracturing operation, is injected back into the Earth for storage, often in underground injection control (UIC) wells.

Dehydrator – Equipment that removes water from natural gas.

Development phase – The phase of petroleum operations that occurs after exploration has proven successful, and before full-scale production. For the purposes of this report, development includes exploration, site preparation, vertical and horizontal drilling, hydraulic fracturing, well completion in preparation for production, and associated waste management.

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 circulating fluid, one function of which is to lift cuttings out of the wellbore and to the surface. It also serves to cool the bit and to counteract downhole formation pressure.

Drill rig – The machine used to drill a wellbore. In onshore operations, the rig includes virtually everything except living quarters. Major components of the rig include the mud tanks, the mud pumps, the derrick or mast, the drawworks, the rotary table or topdrive, the drillstring, the power generation equipment, and auxiliary equipment.

Dry gas – Gas produced from a well that produces little or no gas condensate or reservoir liquids.

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.

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 – Fluid (such as gas, oil, or water) that exists in a subsurface formation.

Flare – A tall stack equipped with burners used as a safety device at wellheads, refining facilities, gas processing plants, and chemical plants. Flares are used for the combustion and disposal of combustible gases. The gases are piped to a remote, usually elevated, location and burned in an open flame in the open air using a specially designed burner tip, auxiliary fuel, and steam or air. Combustible gases are flared most often due to emergency relief, overpressure, process upsets, startups, shutdowns, and other operational safety reasons. Natural gas that is uneconomical for sale is also flared. Often natural gas is flared as a result of the unavailability of a method for transporting such gas to markets.

Flowback water – 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.

Frac pumps – A high-pressure, high-volume pump used in hydraulic fracturing treatments.

Fracturing fluid – The water and chemical additives used to hydraulically fracture the reservoir rock, and proppant (typically sand or ceramic beads) pumped into the fractures to keep them from closing once the pumping pressure is released.

Fugitive emission – Intentional or unintentional release of volatile chemicals during extraction, processing, and delivery of fossil fuels to the point of final use.

G

Gas – *See* Natural gas.

Gas condensate – Hydrocarbon liquid dissolved in saturated natural gas that comes out of solution when the pressure drops below the dewpoint.

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.

H

Habitat fragmentation – Breaking up a contiguous area of habitat as a result of land use, such as roads, pipelines, and other pathways.

Habitat loss – The direct loss of habitat resulting from the footprint of well pads and other infrastructure.

Hazardous air pollutants – These compounds are referred to throughout the report as air toxics.

High-emitters – Facilities that have temporary abnormally high emissions that are caused by an equipment malfunction, accident, operator error, or some other unintended failure of a process to operate in a normal or usual manner. Sometimes referred to as super-emitters.

Horizontal or directional drilling – Deviation of a wellbore from vertical toward a horizontal inclination in order to intersect targeted fractures or maximize contact with a productive formation.

Hydraulic fracturing – A stimulation treatment routinely performed on oil and gas wells in low-permeability reservoirs. Specially engineered fluids are pumped at high pressure and rate into the reservoir interval to be treated, causing a vertical fracture to open. The wings of the fracture extend away from the wellbore in opposing directions according to the natural stresses within the formation. Proppant, such as grains of sand of a particular size, is mixed with the treatment fluid to keep the fracture open when the treatment is complete. Hydraulic fracturing creates high-conductivity communication with a large area of formation and bypasses any damage that may exist in the near-wellbore area.

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.

I

Impact – Adverse changes that might harm human health and well-being, communities near OGD, ecological health, or the environment.

Induced seismicity – Earthquakes related to human activities. Events are typically small in magnitude and intensity of shaking.

L

Liquids unloading – Removal of accumulated fluids from mature gas wells to maintain production.

M

Marcellus shale – An organic carbon-rich black shale that underlies an area of approximately 95,000 square miles along the Appalachian Basin.

Mud – *See* Drilling mud.

N

Natural 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 be associated with oil.

Natural gas field – A region or area that possesses or is characterized by natural gas.

Natural gas liquids – Those hydrocarbons in natural gas that are separated from the gas as liquids through the process of absorption, condensation, adsorption, or other methods in gas processing or cycling plants. Natural gas liquids include natural gas plant liquids (primarily ethane, propane, butane, and isobutane) and lease condensate (primarily pentanes produced from natural gas at lease separators and field facilities).

NORM (Naturally Occurring Radioactive Materials) and TENORM (Technologically Enhanced NORM) – NORM is any terrestrial material (rock, soil, or water) that contains elements that emit radiation. TENORM is produced when activities such as OGD concentrate or expose radioactive materials that occur naturally in ores, soils, water, or other natural materials. For example, barium and strontium scales may be deposited in the wellbore or production tubulars depending on the geological formation and other factors.

O

Oil – A naturally occurring complex liquid hydrocarbon that, 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 or gas field – The surface area overlying an oil or gas reservoir or reservoirs. Commonly, the term includes not only the surface area but also the reservoir, wells, and production equipment.

Oil wells – A well completed for the production of crude oil from at least one oil zone or reservoir.

Open hole – The uncased portion of a well. All wells, at least when first drilled, have open-hole sections that the well planner must contend with. Prior to running casing, the well planner must consider how the drilled rock will react to drilling fluids, pressures, and mechanical actions over time. The strength of the formation must also be considered. A weak formation is likely to fracture, causing a loss of drilling mud to the formation and, in extreme cases, a loss of hydrostatic head and potential well control problems. An extremely high-pressure formation, even if not flowing, may have wellbore stability problems. Once problems become difficult to manage, casing must be set and cemented in place to isolate the formation from the rest of the wellbore. Although most completions are cased, some are open, especially in horizontal or extended-reach wells where it may not be possible to cement casing efficiently.

Orphaned well – Orphaned wells have no known or solvent owner and may or may not be capable of further production.

P

Particulate matter (PM) – A small, discrete mass of solid or liquid matter that remains individually dispersed in gas or liquid emissions. Particulates take the form of aerosol, dust, fume, mist, smoke, or spray. Each of these forms has different properties.

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 bullet-shaped charges that are electrically detonated from the surface.

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

Physical agents – Dust, silica, radiation, and vibration are examples of physical agents.

Physical hazards – Events that may cause illness or disease that are not related to chemical or sensory stressors or to physical agents. Examples of physical hazards are fall hazards, heat stress, traffic accidents, and other incidents.

Play – An area in which hydrocarbon accumulations or prospects of a given type occur. The shale gas plays in North America, for example, include the Barnett, Eagle Ford, Fayetteville, Haynesville, Marcellus, and Woodford.

Potable water – Water suitable for drinking.

Porosity – The percentage of pore volume or void space. Also that volume within rock that can contain fluids. Porosity can be a relic of deposition (primary porosity, such as space between grains that were not compacted together completely) or can develop through alteration of the rock (secondary porosity, such as when feldspar grains or fossils are preferentially dissolved from sandstones). Porosity can also be generated by the development of fractures (fracture porosity). Although shale gas reservoirs tend to have relatively high porosity, but the alignment of platy grains, such as clays, makes their permeability very low.

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

Production – The phase of the petroleum industry that deals with bringing the well fluids to the surface and separating them as well as with storing, gauging, and otherwise preparing the product for distribution. For the purposes of this report, production includes extraction, gathering, processing, and compression of gas; extraction and processing of oil and natural gas condensates; management of produced water and other wastes; and operation of gathering pipelines.

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

R

Reclamation – Restoring a well pad, road, or other landscape impacted by OGD to its original condition.

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 – 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.

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.

Restoration – *See* Reclamation.

Rig – *See* Drill rig.

S

Sediment – The matter that settles to the bottom of a liquid; also called, for example, tank bottoms or basic sediment.

Sensory stressors – Stressors that include odor, noise, and light.

Separator – Production equipment that separates 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 means of gravity (the heavier liquids falls to the bottom and the gas rises 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 natural 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 natural gas can flow out of the well.

Shale gas – Natural gas that can be generated and trapped within shale units.

Source rock – Rocks containing relatively large amounts of organic matter that is transformed into hydrocarbons.

Staged hydraulic fracturing – Hydraulic fracturing that occurs sequentially in several stages along a horizontal well bore (sometimes referred to as “staged treatments”).

Strata – Layers of sedimentary rock.

Stray gas – Gas contained in the geologic formation outside the wellbore that may be mobilized by drilling or hydraulic fracturing, migrate naturally along fractures, or enter an uncased (in bedrock) drinking-water well.

Stressor – A change to the environment that might lead to adverse impacts.

T

TENORM – *See* NORM (Naturally Occurring Radioactive Materials) and TENORM (Technologically Enhanced NORM)

Tight gas – Natural gas trapped in a highly mixed formation of sandstone, shale, or limestone, which has very low permeability and porosity. Although conventional natural gas accumulations, once drilled, can usually be extracted quite readily and easily, gas in a tight formation requires a great deal more effort, including hydraulic fracturing, to extract it.

Tight rock – A relatively impermeable reservoir rock from which hydrocarbon extraction is difficult. Reservoir rock can be tight because it has smaller grains or matrix between larger grains or because it consists mostly of silt- or clay-sized grains, which is the case for shale reservoirs.

U

Unconventional hydrocarbon formation – A formation with relatively low permeability (e.g., the Marcellus and Utica shales), in which the oil or gas does not flow readily into wellbores without the application of a well-stimulation technique, such as hydraulic fracturing.

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.) What qualifies as “unconventional” at any particular time is a complex of resource characteristics, available exploration and production technologies, 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

Waste impoundment – A man-made excavation or diked area for the retention of waste fluids.

Well-being – There is no consensus on a single definition of well-being, but there is general agreement that at a minimum, well-being includes the presence of positive emotions and moods (e.g., contentment or happiness), the absence of negative emotions (e.g., depression or anxiety), satisfaction with life, fulfillment, and positive functioning. In simple terms, well-being can be described as judging life positively and feeling good. For public health purposes, physical well-being (e.g., feeling very healthy and full of energy) is also viewed as critical to overall well-being.

Wellbore – A borehole; the hole drilled by the bit.

Wellbore integrity – The state in which gas and fluid from outside or inside (e.g., injected or produced fluid) the wellbore do not unintentionally enter or migrate from one point to another along the wellbore, especially into drinking water aquifers or the atmosphere.

Well completion – The activities and methods necessary to prepare a well for the production of oil and natural 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 (i.e., the heavy, flanged steel fitting connected to the first string of casing), tubing head (i.e., a flanged fitting that supports the tubing string, seals off pressure between the casing and the outside of the tubing, and provides a connection that supports the Christmas tree), and Christmas tree (i.e., control valves, pressure gauges, and chokes assembled at the top of a well to control flow of oil or gas after the well has been drilled and completed).

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 – A treatment performed to restore or enhance the productivity of a well. Stimulation treatments fall into two main groups, hydraulic fracturing treatments (*See* Hydraulic fracturing) and matrix treatments (e.g., acid or solvent and chemical treatments to improve the permeability of the near-wellbore formation). Fracturing treatments are performed above the fracture pressure of the reservoir formation and create a highly conductive flow path between the reservoir and the wellbore. Matrix treatments are performed below the reservoir fracture pressure and generally are designed to restore the natural permeability of the reservoir following damage to the near-wellbore area. Stimulation in shale gas reservoirs typically takes the form of hydraulic fracturing treatments.

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

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APPENDIX E: 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 Center*
William (Bill) M. Kappel, *Hydrogeologist Emeritus, U.S. Geological Survey*
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 Professor of Civil and Environmental Engineering and Earth and Environmental Science at Vanderbilt University. He is also 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 B.S. and M.S. from Drexel University and his Ph.D. in hydrology from Stanford University.

Alison C. Cullen is a Professor at the Daniel J. Evans School of Public Policy and Governance 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 B.S. in civil/environmental engineering from MIT and an M.S. and Sc.D. 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 Ph.D. 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 his M.D. from Wayne State University and M.Sc. 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, patient or community groups regarding occupational and environmental health, and to 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 B.S. in biology from the University of Notre Dame, his M.S. in zoology from Arizona State University, and his Ph.D. in entomology from the University of California. In 1998, he was a Fulbright Senior Scholar at Institut für Zoologie und Limnologie, Universität 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 B.S. in physical sciences from Pennsylvania State University, and his M.S. 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 Ph.D. 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 socioeconomic 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 United States, 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 bachelor's and master's 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. His 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 B.S. in civil engineering from Stanford University and an M.S. and Ph.D. 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 U.S. 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 Professor Emeritus of Science, Technology, and Public Policy in the Humphrey School of Public Affairs, and Professor Emeritus 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 B.A. in chemistry from Grinnell College. At the University of Wisconsin-Madison, she received an M.S. in water chemistry and a Ph.D. in limnology and oceanography. After two years of post-doctoral research in chemistry and public and environmental affairs at Indiana University, she joined the University of 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 United Kingdom, 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 and Duke's Global Health Institute. Dr. Zhang joined the Duke Faculty in 2013 after being at 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

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.

Alan Krupnick is the co-director of the Center for Energy and Climate Economics (CECE) and a Senior 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 USEPA and the National Academy of Sciences, and has co-chaired a federal advisory committee to the USEPA 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 other publications from 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 B.A. from Pennsylvania State University and his M.A. and PhD. in economics from the University of Maryland.

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 worldwide 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.