Joint US-UK Workshop on Improving the Understanding of the Potential Environmental Impacts Associated with Unconventional Hydrocarbons

5-6 November 2015
Arlington, Virginia, USA

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<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>BB</td>
<td>broad band</td>
</tr>
<tr>
<td>CBM</td>
<td>coalbed methane</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>methane</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>carbon dioxide</td>
</tr>
<tr>
<td>EA</td>
<td>Environment Agency (England)</td>
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<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>GHG</td>
<td>greenhouse gas(es)</td>
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<tr>
<td>HC</td>
<td>hydrocarbon</td>
</tr>
<tr>
<td>HF</td>
<td>hydraulic fracturing</td>
</tr>
<tr>
<td>LCA</td>
<td>life-cycle assessment</td>
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<tr>
<td>LCC</td>
<td>life-cycle cost(s)</td>
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<tr>
<td>LCS</td>
<td>life-cycle system(s)</td>
</tr>
<tr>
<td>NERC</td>
<td>Natural Environment Research Council</td>
</tr>
<tr>
<td>NOx</td>
<td>nitrogen oxides</td>
</tr>
<tr>
<td>NORM</td>
<td>naturally occurring radioactive material</td>
</tr>
<tr>
<td>NSF</td>
<td>National Science Foundation</td>
</tr>
<tr>
<td>PM</td>
<td>particulate matter</td>
</tr>
<tr>
<td>RCUK</td>
<td>Research Councils UK</td>
</tr>
<tr>
<td>RRC</td>
<td>Railroad Commission (regulatory agency in Texas)</td>
</tr>
<tr>
<td>SP</td>
<td>short period (seismicity sensors)</td>
</tr>
<tr>
<td>TDS</td>
<td>total dissolved solids</td>
</tr>
<tr>
<td>UCG</td>
<td>underground coal gasification</td>
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<tr>
<td>UK</td>
<td>United Kingdom</td>
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<tr>
<td>US</td>
<td>United States</td>
</tr>
<tr>
<td>VOC</td>
<td>volatile organic compound(s)</td>
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ACKNOWLEDGEMENTS

We gratefully acknowledge the US National Science Foundation (NSF), the UK Natural Environment Research Council (NERC), and the Environment, Sustainability and Energy Division of the Royal Society of Chemistry (RSC) for providing funding for this workshop and for their further contributions to its organization. We also thank Anna Gest and her team at Virginia Tech Research Center in Arlington for their seamless coordination of facility logistics.

We further gratefully acknowledge all who took part in the workshop – the organizing committee, presenters, formal commenters, and all who participated in the technical discussions and development of research priorities. We especially appreciate the contributions of those who helped capture the discussion points, including Margaret Macdonell, Meagan Mauter, Mitch Small, Soraya Honarparvar, Blanche Wynn-Jones, Stephen Elsby and Pete Edwards. We are also grateful for the assistance of those that provided review comments, including Geoff Hammond, Will Fleckenstein, James Rose, Steve Thompsett, Christopher Franklin, Sarah Keynes, Nichole Saunders, Clare Bond, Mindy Dulai, Frederick Coulon, and Richard Haut.

The content of this report reflects the contributions of each participant. The wording and emphasis in this report is that of the authors and may not reflect the views of the delegates or of the workshop funders.
**1 INTRODUCTION**

Most national energy programs are designed to guide energy production to meet population demand, sustainability and energy security. The deployment of hydraulic fracturing technology to exploit shale oil and gas reservoirs in the USA and now potentially in the UK has raised a number of environmental concerns. Through technological innovation related to hydraulic fracturing and horizontal drilling techniques, oil and natural gas production in the United States has been transformed. Other countries, including the UK, have recognised the potential of this energy resource. Extracting resources from shales and tight geological formations can also contribute to meeting future demand and support the pursuit of energy independence. Natural gas production enabled by hydraulic fracturing, could provide an opportunity to expand hydrocarbon energy resources in a manner that could reduce the carbon footprint of the energy system by replacing coal and oil use for energy production. Hydraulic fracturing for natural gas could thus provide a transitional fuel to a more sustainable energy future. As with any evolving energy resource, in addition to considering the benefits of this technology there is also a critical need to undertake analysis of the potential environmental impacts to gain understanding of the associated hazards and risks and their mitigation. Note that the term “environmental impacts” extends from the natural and physical to social and economic components of our environment.

A workshop funded by the US National Science Foundation (NSF), the UK Natural Environment Research Council (NERC) and the Environment, Sustainability and Energy Division of the Royal Society of Chemistry (RSC) was convened to explore the environmental impacts of unconventional oil and gas activity and identify knowledge gaps and research needs to address those impacts. This report summarizes the discussions and findings of the experts that attended the workshop which was held 5-6 November 2015 in Arlington, Virginia, US.

**1.1 PURPOSE AND SCOPE OF THE WORKSHOP**

The US and UK organized the joint workshop on environmental impacts of unconventional oil and gas development to share experiences and what gaps need to be addressed for a complete understanding, especially in the UK. The US has been employing hydraulic fracturing and related technologies to exploit oil and gas resources for several decades and evaluating the associated environmental hazards and risks has been part of the planning and implementation process. Considerable insights have been gained regarding environmental concerns, and research is ongoing to better understand and mitigate adverse effects.

Research and knowledge gaps may be in terms of a need for discovery research (pure or basic research aimed at acquiring new knowledge about the natural world), applied research (more goal directed and aimed at achieving specific objectives and outcomes) or translational research (aiming to bridge discovery and applied research – i.e. research carried out with the expectation that it will produce a base of knowledge likely to form the background to the solution of current or future problems or possibilities). These gaps may be addressed by new fundamental research, or through innovative application and translation of existing science outputs (data, knowledge and skills) where available.

Compared with the US, the UK is at a much earlier stage of the process in evaluating the impacts of the potential extraction of oil and gas energy resources by unconventional means. There is a commercial desire to develop these resources in the UK, although only a very small number of basins have been identified as
targeted shale reservoirs. The joint US-UK workshop was designed to provide an opportunity for the UK to learn from the considerable US experience, and in particular to understand the measures that are being put in place to avoid adverse environmental impacts, engage with communities, monitor the environment for adverse impacts, and initiate remedial actions. The workshop provided the US participants with perspective and insight from the emerging UK experience and industry regulation, as well as from other US attendees.

The scope of the workshop focused on oil and gas extraction that uses hydraulic fracturing and related technologies as the primary method for increasing permeability, and hydraulic permeability enhancement for shale and other tight formations, both on shore and off shore. Topics not addressed include flooding of conventional reservoirs, underground coal gasification, coalbed methane, and issues related to processing hydrocarbons or transporting hydrocarbon products outside of the area of their production.

1.2 WORKSHOP OBJECTIVES AND FORMAT

The primary objective of this workshop was to identify the current status of research and knowledge gaps related to research into the environmental consequences of hydraulic fracturing for oil and gas production. This should help identify opportunities for research and knowledge translation as well as priority areas for future research and innovation that could help lead towards a better understanding of the environmental consequences of hydraulic fracturing and approaches for the mitigation of adverse consequences. A further objective was to provide an opportunity for US and UK researchers to strengthen collaborations between the countries and across disciplines, promoting a whole-systems approach for this important area.

The workshop program (developed by the organizing committee, led by Danny Reible and Richard Davies) was structured to facilitate the sharing of knowledge and experience from each country across five impact topics. The approach involved introducing each topic with a state-of-knowledge presentation by selected US and UK experts, outlining the status and perspectives for each country and highlighting similarities and differences, as well as important knowledge gaps and research needs. Additional topical experts were then asked to offer commentary on the gaps and needs raised by the presenters, followed by an open group discussion among all participants.

Summary points from the discussions were captured electronically and key points were also recorded in writing. At the end of each day, all participants were given an opportunity to reflect on that day’s discussions and identify a top research priority for the near term (within a year) and one for the longer term (within the next ten years). Danny Reible and Richard Davies then grouped these notes by category to determine key themes for these “top” inputs.

1.3 REPORT ORGANIZATION

This report is organized as follows:

- Chapter 2 describes the scope of the technical sessions and provides highlights of the presentations within each theme, emphasizing knowledge gaps and research needs.

- Chapter 3 summarizes the top priorities for near-term and longer-term research identified by the workshop participants.
• Chapter 4 presents the main findings of the workshop

• Chapter 5 lists the references cited in this report.

• Appendix A outlines the workshop program.

• Appendix B provides the technical presentations given at the workshop.

• Appendix C presents the complete list of “top near-term and longer-term research priorities” identified by participants.

• Appendix D lists the workshop participants, including the co-lead organizers and contributors.
CHAPTER 2 - TECHNICAL PRESENTATIONS

The themes addressed by the five technical sessions at the workshop are described in Section 2.1. Highlights of the US and UK presentations are summarized in Section 2.2.

2.1 SCOPE OF THE TECHNICAL SESSIONS

The workshop began with an outline of the objectives of the workshop by NERC, NSF and Richard Davies. The discussions were then initiated with an overview presentation on the status of hydraulic fracturing in the US and UK by Danny Reible. The topics discussed in each of the subsequent sessions are summarized below.

Whole systems approach to examining the use of unconventional hydrocarbons in the energy system
This topic was focused around developing a better understanding of the community impacts of exploiting unconventional hydrocarbons. It also considered environmental, economic and welfare trade-offs that arise from using unconventional hydrocarbons; community acceptance or non-acceptance; the effects of lock-in and path dependency on energy infrastructure investment; valuing and accounting for natural capital under various future energy scenarios, and linking hydraulic fracturing to changes in ecosystem service provision (and valuing those changes).

The earthquake question for the US and the UK
Earthquakes can be triggered or induced by the hydraulic fracturing process itself or by the injection of the waste flowback water produced by the hydraulic fracturing process. The session considered the most recent research in this area in the US and the UK and the similarities and differences that exist in terms of geology, monitoring density and regulations (i.e. waste water injection). The session also considered the challenges of predicting earthquakes, particularly the potential maximum intensity of an earthquake and how to monitor for both baseline conditions and low intensity earthquakes that might be used to indicate potential hazards.

Protecting air quality
Air quality issues discussed included greenhouse gases (methane) as well as air toxins and effects of emissions on regional air quality (e.g. ozone). The session focused on the most recent research in this area in the US and the UK and identifying similarities and differences between the two countries. Current monitoring programs underway in the US and the UK were discussed and needs for baseline monitoring identified.

Managing water quality and availability
The development of unconventional oil and gas resources can affect both water quality and quantity. Stresses on water availability are particularly acute in the western US in some of the areas undergoing rapid development. In the UK regulation is in place but it is uncertain at this stage what the demand will be and whether it can be met. Potential risks to water quality due to subsurface migration, leaks and failures during transfer to the surface and spills at the surface were explored. The most recent research in this area in the US and the UK were identified with similarities and differences cited. Given the UK has very little experience with water use and contamination from unconventional oil and gas activity, the US experience was used to help identify key directions for research and data collection in the UK. An area where the UK has made significant progress is in establishing environmental baseline monitoring programs and requirements ahead of any significant industrial activity.
Wastewater treatment, disposal and reuse

One of the most important concerns for the development of unconventional resources is the appropriate management of flowback and produced water. Key differences were identified between the US, where most produced water is disposed of by deep well injection, and the UK, where deep well disposal is not currently an option. Treatment and reuse of the flowback and produced water mitigates both water availability and water quality concerns and the potential for such treatment and reuse was explored. The most recent research and innovation particularly in the US, was used to identify similarities and differences and identify opportunities for the UK.

2.2 PRESENTATION HIGHLIGHTS

Key points from the technical presentations are highlighted in Table 2.2, emphasizing the status and perspectives particularly relevant to knowledge gaps and research priorities, and opportunities for translation/application of existing knowledge, data and skills to help address these/inform relevant decision making. (See Appendix B for the presentations.)
<table>
<thead>
<tr>
<th>Presenters per Session</th>
<th>Status and Perspectives</th>
<th>Knowledge Gaps, Research Needs and Translation Opportunities</th>
</tr>
</thead>
</table>
| I Whole-systems approach | Gene Theodori (Sam Houston State University) | • Perception controls attitudes and actions  
• Need for transparency in communication  
• Risks exist and should not be downplayed  
• Often local government officials trusted less than industry  | Need for interdisciplinary research AND outreach  
• Safe uses for produced water  
• Effects of boom and bust cycles  
• Effects of individual versus community wealth creation  
• Relationship of psycho-social disruption and health |
|  | US | • Perception controls attitudes and actions  
• Need for transparency in communication  
• Risks exist and should not be downplayed  
• Often local government officials trusted less than industry  | Need for interdisciplinary research AND outreach  
• Safe uses for produced water  
• Effects of boom and bust cycles  
• Effects of individual versus community wealth creation  
• Relationship of psycho-social disruption and health |
|  | UK | Whole energy systems seeks a better understanding of environmental, socio-economic, physical, natural and biological systems at all time and space scales  
• Effect of energy development scenarios on human capital and ecosystem services  
• Conceptual frameworks and models to integrate UK energy paths to valuation of natural capital | Effect of energy development scenarios on human capital and ecosystem services  
• Conceptual frameworks and models to integrate UK energy paths to valuation of natural capital |
|  | Rob Ward (British Geological Survey) | Focus on baseline monitoring and public perceptions and attitudes towards this. Key points:  
• Need to engage community early and often  
• Diverse approaches may be required  
• Provide timely up-to-date information and regularly  
Keep it personal and understandable | Effective community engagement approaches were identified |
|  | Mike Bradshaw (University of Warwick) | • Strong central government support, little progress in UK  
• Local government and public support split  
• Lack of a clear social license to operate | Need for transparent and credible monitoring of risks and impacts |
| II The earthquake question | US | Jon Olson (University of Texas) | • Rapid increase in quakes with oil and gas development associated with increases in conventional water flood development and deep well injection of wastewater  
• Limited ability to predict seismicity  
• Lack of transparency perceived by public  | Better subsurface characterization  
• Better monitoring of events  
• Prediction of where and when (time lag) as a function of key controlling parameters (rate, pressure, volume, gradients)  
• Ability to estimate potential maximum seismic event |
|  | UK | Mike Kendall | • Lack of wastewater injection limits sources of induced  | Can maximum magnitude be forecast?  
• What is needed for baseline monitoring? |
| (University of Bristol) | Seismicity | Setting appropriate threshold for red light monitoring?  
| | • Mining has been linked to induced seismicity in UK  
| | • First fracturing well led to seismic events  
| | What causes fault reactivation?  
| | Better characterization- fracture monitoring  
| III Protecting air quality |  
| US David Allen (University of Texas) | Potential source of ozone precursors, air toxics and greenhouse gases  
| | • Source monitoring (bottom-up) often differs w/regional monitoring (top-down)  
| | • Super emitters important  
| | Effect of emissions in regional context  
| | Evaluate potentially offsetting effects due to fuel change in power generation  
| | Identify air toxics – what, how much and how?  
| | Relationship of emissions to subsurface chemistry  
| UK Grant Allen (University of Manchester) | Urban background more important in UK  
| | • Background and source apportionment important  
| | • Greenhouse gases but also other constituents  
| | • Multiple time and spatial scale of concern  
| | Potential air quality impacts and their mitigation  
| | Importance of fugitive emissions and their mitigation  
| | Extrapolation of local baselines to broader representative footprints  
| IV Water quality and availability |  
| US Avner Vengosh (Duke University) | Water needed often in water-scarce areas  
| | • Stray gas contamination of groundwater, typically due to well integrity problems  
| | • Spills, leaks, disposal of wastewater at or near surface  
| | • Toxic radioactive residues  
| | • Focus on fracturing fluids may be misplaced  
| | Baseline monitoring and monitoring to detect contamination and source  
| | • Regulatory and monitoring framework to identify and control problems  
| | • Better geochemical tools to support the monitoring  
| UK Rob Ward (British Geological Survey) | All groundwater requires protection including as a future resource (regulatory position)  
| | • Minimal impacts of water demand on water availability at national scale but a local scale may be restrictions  
| | • Baseline monitoring underway before any activity. Results showing the importance of a good baseline  
| | Better deep subsurface characterization to understand contamination pathways  
| | Long-term risk potential of contamination (whole life) need to be assessed – not just during drilling and hydraulic fracturing, e.g. long-term well integrity, environmental disturbance  
| | Detailed characterization of baseline aquifer conditions required at the right spatial and temporal scales and for right parameters (indicators)  
| V Wastewater treatment, disposal, reuse |  
| US Radisav Vidic (University of Pittsburgh) | Reuse of waste water in Marcellus shale play driven by lack of disposal options  
| | • Experience has shown substantial reuse is viable  
| | • Eventually reuse demand will cease  
| | Improve options for reuse by understanding quality requirements and improving chemical additives to overcome quality constraints  
| | Develop technologies for produced water management when reuse is no longer feasible |
| UK | Frederic Coulon  
    | (Cranfield University) | • No wastewater disposal by deep well injection in UK allowed (currently)  
    |                  | • Goal is elimination of liquid disposal by minimizing water use and treating wastewater to conventional treatment work standards (US experience has shown difficulties with this approach)  
    |                  | • Carbon dioxide potential alternative to water for hydraulic fracturing | • On-site integrated shale gas waste water treatment  
    |                  |                   | • Water use reduction – enhanced chemistry and water technology  
    |                  |                   | • Use of alternative extraction fluids to reduce water footprint  
    |                  |                   | • Development of a zero liquid discharge (does not include liquid discharge that can be transported to conventional treatment works)  
    |                  |                   | • Management of subsurface effects of retained fracturing fluids |
CHAPTER 3 - KEY RESEARCH GAPS AND QUESTIONS

3.1 SOCIETAL CONSIDERATIONS - SYSTEMS ISSUES

3.1.1 Social and economic impacts

A better understanding of the potential socioeconomic impacts of unconventional oil and gas development at the local scale is required. Among these are the longitudinal changes (changes identified over a period of time with the same group) in public attitudes to hydraulic fracturing. For example in the US there is evidence now for the impacts of both the effects of rapid growth in the industry (booms) and slowdowns associated with low prices (busts) and the potential consequences. The UK or developing areas of the US would benefit from more research on those consequences. More research on impact of the “bust” phase in the US is needed due to the sizable role oil and gas development has had on some local communities. Given the differences in planning, the role of the UK in the broader EU energy market and the likely limited significance of unconventional oil and gas development in any given community, such boom and bust cycles may not have a substantial impact in the UK.

In both a US and UK context, further research on the relative distribution of benefits and costs would be helpful. In particular, what is the equity of benefit-cost distributions? Despite the lack of commercial development in the UK at present, there is good reason to think that they could be significantly different in the UK than in the US. This because of the lack of private ownership of mineral resources and the fact that the UK is part of a much larger EU gas market that will limit the impact of UK production on domestic gas prices. Similar situations occur in the US in certain states. Research into the differences between public perception of cost versus benefits in a northeastern state, where private ownership of mineral resources is less common, to western states where resources are commonly privately owned, may be useful.

There exists significant uncertainty in the economic outlook for unconventional oil and gas development, at least in the short term. The future cost of oil and gas resources could substantially change the economic incentives for unconventional development and exporting unconventional resources. The costs of meeting environmental imperatives, e.g. treatment of flowback and produced water which may be required in the UK, may substantially reduce or eliminate economic incentives for unconventional oil and gas development.

A whole life cycle approach is needed to fully understand the costs and benefits of unconventional oil and gas development, recognizing both economic and environmental issues and benefits, and comparisons to alternative energy sources. An overly narrow perspective will not fully identify the potential costs of development. A challenging component of this may be that whole life cycle analyses of some energy technologies may not be as well developed as others, creating inaccurate comparisons of relative costs and benefits.

3.1.2 Decision processes

There are significant differences between the decision making process in the UK and US. In the UK there is a national government policy (hydrocarbon licensing, planning policy and environmental regulation) and EU policy, although local planning decisions influence policy as well. There is some devolved decision making, for example, the ability to impose moratoria. In the US, much of the environmental regulation of oil and gas activity is controlled by the states, and state policies are highly variable. For example New York State and Pennsylvania have different policies for exploitation of the same formation – the Marcellus Shale, with New
York choosing to limit development and Pennsylvania actively encouraging development. One research gap is the empirical information on the nature of government-industry-public interactions regarding shale gas development permitting and regulation to-date. Has a transparent, open, participatory process for shale gas siting, operations, monitoring and benefits-sharing been deployed and could it be done?

Research into multi-criteria decision analysis may prove useful. Multi-criteria decision analysis recognizes that costs and benefits are valued differently by different sectors and rarely is any one criterion sufficient to drive decisions. There is a need to better understand how to make sense of disparate multi-modal data to make regulatory and management decisions and compare practices in a way that is more data driven and efficient. This inherently raises the issues of ‘trade-offs’ and there is a need for a broad life-cycle view of unconventional oil and gas development and its potential economic benefits and environmental costs.

3.1.3 Approaches for engagement

These was a call for research on the most effective approaches for better engaging communities in order to provide the public with the information they need to understand and evaluate the potential environmental impacts of hydraulic fracturing. This can be seen as a need for research on the approaches being used in engagement, and which approaches were most successful in developing a good understanding of issues and concerns among the public to better enable their engagement in policy and management decisions.

3.1.4 Characterizing multiple stressors

There are multiple stressors, such as air pollutants, naturally occurring radioactive material (NORM), waste water treatment residuals, noise, and light pollution. Health effects and air quality impacts associated with sand proppant or synthetic proppants also include related issues with NORM and solids management. How do we create a nested/affordable/trustworthy monitoring infrastructure to let us discriminate sources, pathways and context of emissions for all media?

3.1.5 Approaches and tools for exposure and effect assessments

Research is needed into technologies that allow for tracers and bioindicators of exposure and effects. There may be a role for citizen science where citizens support data collection with relatively simple measurement devices. Regardless of methods used, it is important to establish a solid baseline in terms of groundwater quality, air quality, public health, etc. before initiation of unconventional oil and gas development, so that any potential impacts can be identified.

Combined and cumulative effects, including from chronic exposures (e.g. effects of stress on immune and cardiovascular systems), would be of concern to the public. Both a baseline and potential changes due to unconventional oil and gas development would be useful.

The potential human health effects are largely associated with exposures due to air and water releases, and are not likely to be unique to unconventional oil and gas development and hydraulic fracturing. Definition of the potential exposure is thus associated with the ability to define air and water releases, and research to clarify those releases and exposures is paramount.

3.1.6 Integrated and life-cycle assessment models
A broad systems view is required to understand the overall implications of unconventional oil and gas development. The first concern is scale and intensity: to what extent does the geographic scale of hydraulic fracturing in the US, and potentially in the UK, distinguish it from other activities (e.g. mining) that create environmental risks?

Integrated impact assessment and prediction models are needed that can accommodate a variety of data of different quality and scale that covers and combines data key to engineers, physical and social scientists, economists, regulators, and public for system evaluations. Data would include qualitative measures, where this is all that is available, and data collected by civic/citizen scientists, also extending through science/engineering techniques.

Research is needed to establish error bounds on input emissions data for environmental life cycle assessment and integrated assessment tools. Research into the comparative emissions from the range of energy options available to the UK at present is also needed.

The assessment should include full life cycle inputs to avoid an overly narrow evaluation of benefits and potential costs of unconventional oil and gas technologies as well as competitive energy technologies.

3.2 PROTECTING AIR QUALITY

3.2.1 Greenhouse gas emissions

The IPCC (Intergovernmental Panel on Climate Change) recommends the planet should not exceed a 2°C increase in temperature using a pre-industrial baseline and there are efforts to limit this even further. Shale gas and oil could produce CH₄ through the extraction process and other stages in the life cycle as well as CO₂ through burning of these fuels. The benefits of cheap, plentiful natural gas can be lost if there are substantial methane emissions during production and through the supply chain.

There were two main questions relating to this issue. Firstly, what are the total cradle to grave emissions related to shale gas and oil? There are emissions of methane related to the production process in the US (Allen, Torres et al. 2013) and there would be further emissions as gas is transported and potentially cooled and compressed for shipping as LNG, eventually being burnt or used as chemical feedstock outside of the USA.

Secondly, how do these emissions compare to other energy sources? For example comparisons have been made in the past with emissions from the production and burning of coal (Howarth, Santoro et al. 2011). Having reliable data should inform climate change policy (e.g. future conference of parties (COP) negotiations) and allow countries planning to develop shale gas and oil to understand the impact it has on emissions and legally binding emissions targets (e.g. UK).

Methodologically, both the US and UK need to acquire high quality data and need effective techniques for holistic monitoring of the environment. High quality monitoring should mean we can distill and constrain any meaningful parameter (i.e. representability/uncertainty). A major concern is taking short term field program data and extracting representative long-term predictions. The term “super-emitter” has been used to describe the phenomena that a small number of oil and gas sites and components are responsible for the majority of total methane emissions which make representative measurements and predictive estimates difficult. Any evaluation of these emissions will largely have to be limited to the US due to the large number of wells in operation compared to the UK. Any such evaluation, however, will not be able to consider any differences
between US and UK operations due to the small number of UK wells likely to be in operation in the near future that are unlikely to provide statistically valid emissions data.

Ultimately the research question that this addresses is; does shale gas and oil development cause a change in trajectory for CO$_2$ and CH$_4$ targets in the long term? What would our CH$_4$ emissions look like in 10 years with and without mitigation in place?

### 3.2.2 What does the emitting and when?

More monitoring of unconventional oil and gas infrastructure is needed to understand which parts of the system are the biggest emitters and when these emissions occur. There is a gap in knowledge around what equipment the emissions are from, for example are they from tanks, gathering lines or wastewater treatment facilities? Analysis of the typical emissions from existing conventional and unconventional oil and gas infrastructure is needed. It must be recognized that these can vary dramatically due to variations in gas or oil composition and the available infrastructure. In areas where oil is being produced and infrastructure for management of gas is not available, flaring of the excess gas is often used with its resulting impact on emissions and production. Rules on when flaring can be employed and the technologies for flaring may also be quite different across the US, and between the US and the UK. In areas where oil composition contains a significant amount of volatile species, emissions of these species may be higher. In general, emissions from the entire supply chain need to be measured so the full impact is understood. Moreover, these should be compared to entire supply chain emissions from competitive energy sources.

In the US, the term ‘super-emitter’ has been coined to describe the phenomena that a small number of operations associated with extraction or processing of oil and gas are disproportionate emitters of methane (CH$_4$) and other gases. Current data suggest that there are a small number of operations, equipment and processes that lead to the vast majority of emissions and that ‘super-emitters’ should be the focus of more research. What is the cheapest and most effective technique for isolating and correcting methane super-emitters?

In the UK there is to date no evidence for super-emitters from the existing gas and oil infrastructure. However, there is very limited data regarding fracking related emissions as only one well has been hydraulically fractured in shale (Preese Hall, Lancashire, 2011), which has since been decommissioned.

### 3.2.3 Characterizing a range of gaseous emission

Volatile organic compounds (VOCs) are organic chemicals with a high vapor pressure at room temperature. They have a low boiling point which means they evaporate readily and enter the surrounding air. In the US VOCs have been recorded in conjunction with shale operations. VOCs can be associated with 1) direct releases of VOCs that are part of oil and natural gas (e.g., propane), and 2) formation of VOCs from combustion sources (e.g., formaldehyde). Many of these compounds are toxic or can contribute to other air quality concerns such as tropospheric ozone. VOCs have been associated with shale gas activities in the USA (Bunch, Perry et al. 2014).

The questions raised by attendees were around what VOCs can we expect from different shales in the US and UK. Are there differences for oil vs shale production? Are there episodes of unusual gas emissions related to shale? Are there subsurface processes that could result in the release of compounds not normally found in oil and gas operations? For example, it was reported that there were elevated levels of chlorinated hydrocarbons
in the vicinity of oil and gas activities associated with hydraulic fracturing. Determination of unusual gas emissions could be gained from long-term gas or atmospheric monitoring.

A substantial uncertainty associated with “super-emitters” as well as normal releases is related to the relationship between emissions and management practices. What are best management practices for the control of emissions of volatile organic compounds and how do they change as a function of type of operation and procedures in place during the operation.

3.2.4 Air Quality

Regional air quality (e.g. ozone level) is impacted by emissions from infrastructure and associated traffic movements as well as the oil and gas production itself. The effects are a function of direct emissions, meteorological conditions and secondary processes in the atmosphere. The different meteorology and population density in the UK may lead to substantially different impacts on air quality.

The cumulative impact of unconventional oil and gas activity on air quality including greenhouse effects, ozone, and particulates need to be understood. Specific questions, many of which were identified above, include “What are the halogenated organics in the air around wells?” and “What are the causes of and mitigations for VOCs/NOx emissions from shale sites?”

3.3 WATER USE

3.3.1 Reducing water use and waste water production

Substantial amounts (3-13 million US gallons) of water are used in hydraulic fracturing in the US (King and King 2013). In some portions of the US where there is active fracturing ongoing, water resources are scarce and hydraulic fracturing places an additional strain on those resources (Vengosh, Jackson et al. 2014). Research and innovation is needed to more efficiently use the water that is required. There has been some reduction in the water use intensity in newer wells and research may provide improved efficiencies in the future.

In the US, particularly in the arid west, groundwater or rights to surface water is typically owned by the landowner and thus much of the water used in hydraulic fracturing has resulted in economic benefits to that landowner. This has helped maintain oil and gas activity even in areas of scarce water resources and times of drought. In the UK, regional governments will decide whether water can be diverted to hydraulic fracturing activities, potentially slowing and limiting the availability of water.

The most effective means of reducing water use is through reuse of produced and flowback water. Flowback water is a mix of hydraulic fracturing fluid and formation fluid while produced water is primarily derived from the formation over the entire period of well production. The formation waters are generally of poor quality (dissolved salts > 100,000 mg/L) and require substantial treatment for anything other than reuse for hydraulic fracturing. Reuse for hydraulic fracturing has recently proven successful in the US and can benefit by additional research into chemical additives for controlling viscosity of fracturing fluids. Chemical additives for cross-linked gels are particularly challenging for high salt waters.

The volumes and chemistry of flowback and produced water in the US are highly variable depending on formation. For example, the Barnett shale generally yields more flowback than the Marcellus shale, potentially due to the extension of fracturing into productive aquifers below the zone of natural gas production. This greater flowback water gives rise to significantly greater water management concerns, including transportation
as well as treatment and disposal issues. Much of this water is deep well injected in the United States but there are some areas (Marcellus) where there are limited disposal options which have encouraged recycling of the water. Even with recycling of the water for hydraulic fracturing, there may be a mismatch between production of produced and flowback water, and needs for hydraulic fracturing waters. Reusing water or keeping it downhole, however, may change the potential for surface spills or management issues and may reduce the need for deep well injection and its associated seismicity. There was also discussion on the water requirements and the volumes of wastewater produced, and hence the challenges, during the period of declining development (drilling and fracking) of a field.

In the UK there is very little experience as to the volume of waste water that would be produced as flowback except from conventional oil rather than the very different setting of shales, and therefore the volumes of water that would be subject to disposal or reuse from unconventional sites is unclear. The flowback water from a site (conventional or unconventional) might normally be seen as waste but is still open for recovery and re-use; whereas produced water may be returned to the same formation. The produced water from existing sites therefore can be put back down the well or much more likely, a nearby well that goes to the same formation and in this way provide some enhanced oil recovery.

It would not normally be permissible to put the oil produced water into another other formation (which is allowed in many US states). For this to be considered in the UK the receiving formation would have had to be deemed “permanently unsuitable for use” under the terms of the Groundwater daughter directive. At present the UK does have an approach to tell us about this permanently unsuitable criterion but more clarity is needed and there is work going on with EA to better understand and define this so that by the time any unconventional hydrocarbon industry has become manifest a clearer definition is in place.

In addition, there is all the other water that is produced or collected on a site such as rainfall, surface water run-off, other process waters etc. In some places in the US these are also disposed of down into the formation. For England, these should be dealt with as for any other site but, for example, it may not be very sensible to regulate in detail the fate of the clean rainwater. These topics are being actively considered by the EA and research that addresses them would be timely.

Some produced water will need to be treated. Water treatment can be expensive and in the UK this could have an impact on the economic feasibility of oil and gas development. Treatment is discussed in more detail in the next section although research into alternative disposal options should be evaluated.

Another alternative to freshwater resources for hydraulic fracturing is the use of poor quality brackish or salty waters. Many operational areas in the US have access to poor quality brackish groundwaters with dissolved solids in the 3,000-30,000 mg/L salts that could serve as hydraulic fracturing fluids. Research is needed on the location, productivity and quality of brackish water aquifers that could be used in this way and the additives required to efficiently use this water for hydraulic fracturing.

Research is also needed on the understanding of brine chemistry and its relationship to scaling and precipitation processes as well as hydraulic fracturing fluid properties. There was discussion around the operational and economic challenges with re-using highly saline fracking fluids and also an issue of generating toxic chemicals (e.g. Trihalomethanes - THMs) as a result of reaction with fracking chemicals and/or hydrocarbons.
Other approaches to reducing the use of freshwater for hydraulic fracturing include the use of CO₂ and hydrocarbon gases. The use of CO₂ might be especially beneficial as a means of carbon capture to alleviate greenhouse gas concerns and research into its use and the potential return of CO₂ to the surface is warranted.

### 3.3.2 Water quality concerns

Hydraulic fracturing for unconventional extraction of oil and gas resources has been linked to water quality concerns (Davies 2011, Osborn et al. 2011, Vengosh et al. 2011). While direct connection between most hydraulically fractured aquifers and drinking water supplies is generally not of significant concern, there is the potential for contamination due to casing failures in a drinking water aquifer and spills and mismanagement of flowback and produced water at the surface (e.g. Yale, 2015). The casing failures are generally not directly linked to hydraulic fracturing but can occur in any well as a result of poor construction or completion efforts. Direct connection between fractured formations and drinking water aquifers are also possible when they lie in close proximity. While that is unusual in shale formations, it is more common in some near surface tight producing formations. Regulations recently introduced in the UK will prohibit high volume hydraulic fracturing at depths less than 1000 m based on the maximum measured height of a fracture being 600 m (Davies et al., 2012).

Research is needed to develop procedures for identifying and locating such leaks and aquifer connections as well as technologies to minimize their frequency of occurrence and procedures to mitigate their impacts. A variety of geochemical tracers including noble gases, isotopic analysis of hydrocarbon gases and other means have proven useful in this context but could be further developed for routine use. A key requirement of understanding potential interconnections is to conduct baseline monitoring before the initiation of hydraulic fracturing.

Another source of water quality impacts arising from the flowback and produced water is spills, leaks or mismanagement at the surface. Transportation and treatment of these waters can increase the opportunities for such spills. The primary environmental concern is associated with the concentrations of toxic heavy metals, mon-methane hydrocarbons, naturally occurring radioactive materials (NORM) and chemical transformation products. As well as risks to the environment there are also human health concerns and in both case better research is required. The very high dissolved solids content of these waters also generally limits traditional disposal (e.g. in wastewater treatment plants) or surface water discharges. Best management practices and technologies that reduce the inherent risks of surface spills are appropriate research goals. In addition, appropriate mitigation and remediation strategies for spills once they occur should also also be the subject of research.

### 3.4 WASTE WATER TREATMENT AND DISPOSITION

#### 3.4.1 Waste water characterization

Flowback and produced water is increasingly being used as a hydraulic fracturing fluid. The ability to reuse such water directly depends upon its chemical characteristics that may limit appropriate control of downhole properties and the potential for scaling. The flowback and produced water that are not reused as hydraulic fracturing fluids or to maintain formation pressures must be managed. Often trace constituents may control the use or reuse of these waters. For example, constituents such as barium and strontium may pose concerns about scaling or precipitation (Oddo and Tomson 1994). An understanding of these constituents and their effects on brine chemistry is required to make better decisions about reuse. Potentially toxic effects and
impacts on other media (such as air or soil) may also be controlled by trace constituents (e.g. NORM) in the flowback and produced water (Vidic, Brantley et al. 2013). Finally trace constituents may lead to difficulties in later treatment steps, e.g. bromine on brominated methanes in drinking waters, (Wilson and Van Briesen 2013) and research into their implications is warranted.

3.4.2 Treatment technologies and reuse options

Appropriate treatment technologies for the flowback and produced water that cannot be reused for hydraulic fracturing is an important area of research. At the current time in the US, most flowback and produced water is deep well injected with the consequent effects on seismicity (discussed in the next section), loss of water from the water cycle and the resulting effects on water availability. The treatment required for any particular reuse requires an understanding of the flowback and produced water chemistry and the quality requirements of any particular reuse. A major difficulty is that the cost of deep well injection is relatively low and treatment schemes must compete with that cost. Often this means that simple filtration or settling are the only cost effective means of treatment (Fakhru’l-Razi, Pendashteh et al. 2009). This will not manage NORM, dissolved solids or dissolved toxic components. Research into cost-effective alternative treatments is necessary as well as research into potential applications. Current alternative applications that have been suggested but often not adequately researched include de-icing salts for roads, makeup water for cooling towers (e.g. for power generation) and direct use in salt water ponds (e.g. salt water hydroponics in inland areas or solar salt ponds for electricity generation).

Reuse as a hydraulic fracturing fluid is perhaps the most direct way to use the produced waters but can only continue as long as there are nearby fracturing activities. Research into treatment of water unable to be used in that way should be initiated now.

Deep well disposal is currently not permissible under most scenarios in the UK and that puts additional pressure on research for treatment and reuse of the flowback and produced water. Research is currently being undertaken into how and when deep well disposal or direct reuse as a hydraulic fracturing fluid can be implemented in the UK. A huge uncertainty, given the immaturity of unconventional oil and gas development in the UK, is how much waste water will be produced and regulatory and technical mechanisms for cleaning it or directly reusing it. Without deep well disposal, it is likely that treatment of the dissolved solids will be required and so research into cost-effective means of doing this is important to the implementation of unconventional oil and gas production in the UK.

The costs related to waste water production may be significant and could make shale exploitation uneconomic. Research into potential uses of the flowback and produced water that might require less treatment should be pursued as well as treatment schemes taking advantage of cheap power (e.g. off peak power generation).

In the UK deep disposal is not a currently available option and there is unlikely to be sufficient industrial wastewater treatment capacity to service the needs of a mature operational industry and so there is a pressing need to address this through research and technology development.
3.5 INDUCED SEISMICITY AND THE FATE OF INJECTED WATER

3.5.1 Hydraulic fracturing

Induced seismicity can be the result of both hydraulic fracturing and, more commonly, waste water injection (Hornbach, DeShon et al. 2015). A key question is how fractures propagate away from the wellbore and how does fluid move into a fault zone to trigger seismicity. It should be remembered that poroelastic effects can also stimulate seismicity in the absence of any connecting fractures.

Of major concern is the ability to predict the maximum potential earthquake as a result of hydraulic fracturing. This may be related to the locations of faults, and research into how to detect and avoid faults is an important goal. Moreover how to monitor and respond to earthquakes is required. At the current time, the regulatory threshold for action in the UK may not be able to be measured and therefore the defined threshold is of little benefit. Improvements in measurement technologies are needed or a redefinition of the appropriate threshold based upon empirical evidence. Researchers and regulators in the US are investigating improved management practices to minimize induced seismicity. IOGCC (2015) includes the most comprehensive examination and discussion of induced seismicity in the US to-date.

3.5.2 Waste water injection

In the US, wastewater injection is by far the most important cause of induced seismicity. This is largely not the result of hydraulic fracturing but the disposal of water from both unconventional and conventional oil and gas activities. Some of the most active seismic responses to wastewater injection have been the result of increased oil and gas activity in conventional fields as a result of price pressures.

A better understanding of how to identify and avoid seismic effects and manage those that occur is needed. This includes a better monitoring network for seismic events to identify and locate earthquake activity, as well as improved understanding of how specific wells induce that activity. Data on injection volumes and pressures, improved fault mapping and measurements of the induced seismicity are all needed to better define the relationships.

Of major concern is the maximum potential earthquake. How do we know that waste water injection will not cause big fatal earthquakes? Is there a scenario where such an earthquake could occur? What baseline monitoring is required now to monitor/understand how deformation and fluids lead to seismicity and leakage?

Concern was expressed about the level of information available on the fate of injected waste fluid. Although there is repeat logging of reservoirs others suggested that we know little of how the plume of injected fluid migrates.

Research is also needed into the environmental, economic, social tradeoffs associated with alternative wastewater management and disposal practices. Examples include (1) environmental impacts of limiting use of disposal wells due to potential seismicity, (2) comparing trucks vs. pipelines for management of wastewater. The environmental, social, and cost impacts of these different options should be considered.
CHAPTER 4 - SUMMARY OF FINDINGS AND TRANSLATION OPPORTUNITIES

4.1 SUMMARY OF HIGH LEVEL RESEARCH NEEDS

This table summarizes the knowledge gaps based upon the significance of the environmental impact and the level of scientific understanding.

Table 4.1 US and UK Similarities and Differences by Theme

<table>
<thead>
<tr>
<th>Theme</th>
<th>Knowledge gaps/needs</th>
<th>US or UK or both</th>
<th>Reasoning for urgency (i.e. impact)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Community Engagement</td>
<td>Understanding socio-economic impacts and resulting public perceptions of unconventional oil and gas development.</td>
<td>Both</td>
<td>So that publics can have a say in the scale of unconventional oil and gas development.</td>
</tr>
<tr>
<td>Energy systems</td>
<td>Whole life cycle effects of unconventional oil and gas development and competitive technologies.</td>
<td>Both</td>
<td>What is the information on which an appropriate energy mix can be defined?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>What is the potential for unconventional oil and gas development to provide a transitional path to a carbon free energy future?</td>
</tr>
<tr>
<td>Human Health</td>
<td>Potential effects on human health.</td>
<td>Both</td>
<td>Very early stage. Lack of understanding of long term impacts yet a potentially significant public concern.</td>
</tr>
<tr>
<td>Air Emissions</td>
<td>Monitoring of emissions at shale well pads and related infrastructure.</td>
<td>Both</td>
<td>Reports of health issues related to emissions. Much more acute in the USA. UK existing gas and borehole infrastructure provides baseline pre-hydraulic fracturing.</td>
</tr>
<tr>
<td></td>
<td>Emissions of VOCS, methane, CO2 should be included.</td>
<td></td>
<td>Concerns of greenhouse gas emissions offsetting the positive benefits of natural gas expansion.</td>
</tr>
<tr>
<td></td>
<td>Effect of management practices and super emitters should be included.</td>
<td></td>
<td>Regional air quality impacts that may lead to non-attainment in downwind areas.</td>
</tr>
<tr>
<td>Water Quality</td>
<td>Identifying and locating well leaks and indicators.</td>
<td>Both</td>
<td>To improve leak detection capability and long term protection of the environment.</td>
</tr>
<tr>
<td></td>
<td>Characterisation of sub-surface migration pathways.</td>
<td></td>
<td>To address concerns about human health risks from exposure to fluids in fracking and/or produced during operations.</td>
</tr>
<tr>
<td></td>
<td>Characterisation of produced/flowback water chemistry.</td>
<td></td>
<td>There is a need to evaluate the risks to shallow groundwater and drinking water to support better environmental protection and development of effective regulation.</td>
</tr>
<tr>
<td></td>
<td>Risk assessment and management tool development.</td>
<td></td>
<td>Well defined environmental baseline is required to openly test to the satisfaction of the public as to whether or not environmental damage is occurring</td>
</tr>
<tr>
<td>Waste Water</td>
<td>Prediction of the</td>
<td>UK/US</td>
<td>Deep well disposal not currently an option in the UK. Lack of</td>
</tr>
</tbody>
</table>
4.2 TRANSLATION OPPORTUNITIES

Research needs may be addressed through new fundamental research, or through innovative application and translation of existing science outputs (data, knowledge and skills) where available.

There was no dedicated session on the opportunities for translation of research into policy and commercial value in the environmental industry and to provide a comprehensive listing of all the potential routes for commercial and policy impact is not attempted here. Instead we identify below two areas that reflect the views of the authors after the workshop on the most obvious opportunities for innovation and translation/application of existing research outputs (data, knowledge, skills) associated with environmental protection.

1. There are significant innovation opportunities related to environmental monitoring. Both the USA and UK could develop remote, automated monitoring capabilities at new and existing oil and gas infrastructure. Handling real-time environmental monitoring, ‘dynamic data’, would inform agencies on environmental conditions, before, during and after fracking. Static datasets that are available in the USA and UK could also be used to provide risk assessment tools. This would involve the collection and streaming of vast datasets and converting these into tools that make sense to those that monitor the industry (i.e. operators, environmental agencies, state governmental, councils and national governments). This links into the recent development of the “internet of things” and smart technologies. These translational opportunities could lead to commercial openings for companies working in this space and also mean that data can be more effectively translate into evidence-based policy in the US and UK.

2. In the USA waste water can in many cases be reinjected underground. This cannot be done in the UK unless it is for pressure support in an existing oil field. In places like Pennsylvania reinjection is also not
common. Technologies that reduce the volume flow back water or allow for low cost cleaning of contaminated water or its reuse could be commercially important.
5 REFERENCES


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APPENDIX A: WORKSHOP PROGRAMME

Joint US-UK Workshop on Improving Understanding of Potential Environmental Impacts Associated with Unconventional Hydrocarbons - Meeting Agenda

Note on scope of workshop:

- **Within scope:** any fossil fuel extraction that uses hydraulic fracturing as the primary method for increasing permeability: *i.e.* shale gas and oil, hydraulic fracturing coal seams, tight formations
- **Outside of scope:** water flooding of conventional reservoirs, UGC, CBM, transportation or processing issues.

This workshop will be structured with a presentation of the state of knowledge in each area followed by a discussion session. The final session on each day will include a writing session to initiate the preparation of:

Anticipated outcome is a co-authored (Danny Reible and Richard Davies) report which focuses on identifying new research and data gaps, and opportunities for existing research to be translated, to better understand and therefore mitigate the environmental consequences of hydraulic fracturing for oil and gas production, using a whole systems approach. The report will acknowledge the funders of the workshop (NSF, NERC, RSC) and will be publicly available.

**Day 1 (November 5, 2015)**

7:30 to 8:30  Registration

8:30 to 8:45  Welcoming remarks

- Objectives and outcome (NSF and NERC)
- Workshop Programme/ Process (R. Davies University of Newcastle)

8:45 to 9:00  Status of Hydraulic Fracturing for Oil and Gas Production in the US/UK (D. Reible, TTU)

**Session I: Whole systems approach to examining the use of unconventional hydrocarbons in the energy system**

Scope: Understanding community impacts and environmental economic and welfare trade-offs that arise from using unconventional hydrocarbons, community acceptance and impacts, the effects of lock-in and path dependency on energy infrastructure investment, valuing and accounting for natural capital under various future energy scenarios, linking hydraulic fracturing to changes in ecosystem service provision (and valuing those changes).

9:00 to 9:20  Status and Perspective in the US (G. Theodori, Sam Houston St. Univ)
9:20 to 9:40  Status and Perspective in the UK (Dr. Matthew Agarwala, University of East Anglia, Dr. Rob Ward, British Geological Survey and Prof. Mike Bradshaw, University of Warwick)

9:40 to 10:30  Discussion

10:30 to 11:00  Break

Session II: The Earthquake Question for the US and the UK

Scope: What is the most recent research in this area in the US and the UK? What similarities and differences are there (e.g. geology, monitoring density, regulations (i.e. waste water injection))? What remaining questions exist? Are they important and if so what would it take to tackle them? Are there any specific recommendations in relation to baseline monitoring that can be shared?

11:00 to 11:20  Hydraulic Fracturing and Seismicity in the US (J. Olson, UT)

11:20 to 11:40  Hydraulic Fracturing and Seismicity in the UK (Prof. Mike Kendall, University of Bristol)

11:40 to 12:30  Discussion

12:30 to 1:30  Lunch (on your own or perhaps catered to extend discussion time)

Session III: Protecting air quality

Scope: What is the most recent research in this area in the US and the UK? What similarities and differences are there? What monitoring programmes are underway in the US and the UK and how do the results compare? Are there any specific recommendations in relation to baseline monitoring that can be shared?

1:30 to 2:00  US Experience with air quality and greenhouse gas emissions and their mitigation (D. Allen, University of Texas)

2:00 to 2:15  UK Perspective on air quality and greenhouse gas emissions and their mitigation (Dr. Grant Allen, University of Manchester)

2:15 to 3:00  Discussion

3:00 to 3:15  Break

3:15 to 4:30  Discussion and Writing. This session will capture the key conclusions of the sessions on the whole systems approach to examining the use of unconventional hydrocarbons in the energy system, concerns relating to seismic activity and ground motion and air quality and greenhouse gas concerns. The current understanding and significance of the concerns and research needs in each area will be identified and prioritized. Assignments and timetables for completion of the reports will be defined.

4:45  Break for Reception

Day 2 (November 6, 2015)

Session IV: Managing Risks to Water Quality and Availability

Scope: What is the most recent research in this area in the US and the UK? What similarities and differences are there? Given the UK has very little data on water use what recommendations would the make in ensuring
that this is managed effectively? What critically important research and data collection would the US side recommend for the UK?

8:30 to 8:50  US Experience with Risks to Water Quality and Availability (A. Vengosh, Duke)
8:50 to 9:00  UK Perspectives on Water Quality and Availability (Dr. Rob Ward, British Geological Survey)
9:00 to 9:45  Discussion
9:45 to 10:15  Break

**Session V: Wastewater Treatment, Disposal and Reuse**

**Scope:** What is the most recent research in this area in the US and the UK? What similarities and differences are there between the US and UK? Are there any specific recommendations in relation to baseline monitoring that can be shared?

10:15 to 10:35  US Experience on Wastewater Treatment, Disposal and Reuse (R. Vidic, Univ of Pittsburgh)
10:35 to 10:55  UK Perspectives on Wastewater Treatment, Disposal and Reuse (Dr. Frederic Coulon, Cranfield University)
10:55-11:45  Discussion

11:45 to 12:45  Discussion and Writing. This session will capture the key conclusions of the sessions on water availability and water and wastewater management. The current understanding and significance of the concerns and research needs in each area will be identified and prioritized. Assignments and timetables for completion of the reports will be defined.

12:45 to 1:00  Workshop closure
APPENDIX B: TECHNICAL PRESENTATIONS

1. US UK Workshop: Objectives and Outcome - Sarah Keynes
2. Status of Unconventional Oil and Gas Development - Danny Reible
3. Status and Perspective of Hydraulic Fracturing in the U.S. - Gene L. Theodori
4. Whole Systems approach to unconventional hydrocarbons in the energy system: Uk status and perspective - Matthew Agarwala
5. Public engagement: experience in the UK - Rob Ward
6. Contours of the UK Shale Has Debate - Mike Bradshaw
7. Hydraulic Fracturing and Seismicity in the US - Jon Olson
8. Hydraulic fracturing and seismicity in the UK - Michael Kendall
9. Increased Natural Gas production and Air Quality - David Allen
10. UK Perspectives on air quality, greenhouse gas emissions and their mitigation - Grant Allen
11. United States Experience with Risks to Water Quality and Availability - Avner Vengosh
12. UK Perspectives on Water Quality and Availability - Rob Ward
13. US Experience on Wastewater Treatment, Disposal and Reuse - Radislav D. Vidic
14. The UK perspective on Wastewater Treatment, Disposal and Reuse - Frederic Coulon
US UK Workshop: Objectives and Outcome

Sarah Keynes – NERC Innovation
Blanche Wynn-Jones - NERC Science

5 November 2015
Natural Environment Research Council (NERC)

• NERC is the UK’s leading public funder of environmental science

• We invest £330m each year in cutting-edge research, postgraduate training and innovation in UK universities and research centres
Our remit

• NERC's remit includes earth, energy, atmospheric, terrestrial, marine, freshwater and polar sciences, science-based archaeology, and Earth observation

• Our scientists study and monitor the physical, chemical and biological processes on which our planet and life itself depends
Our vision

To place environmental science at the heart of responsible management of our planet
Workshop

• Joint US-UK Workshop on Improving Understanding of Potential Environmental Impacts Associated with Unconventional Hydrocarbons

• Funded by:
  - NSF
  - NERC
  - Environment Sustainability & Energy Division of the Royal Society of Chemistry (ESED)
Workshop Objectives

• Discuss key science and associated industry and policy/regulatory **challenges** associated with shale oil and gas exploration and extraction

• **Facilitate** networking, discussion and enable researchers to share ideas

• Explore a **whole systems approach** to examining the use of unconventional hydrocarbons in the energy system

• Analyse and define **knowledge gaps, focused scientific research questions** and opportunities for **translation** of existing research
Funding streams

**Discovery Science** Research driven by curiosity - asking fundamental questions about the planet we live on.

**Strategic Research** Providing the understanding to meeting the challenges faced by society.

**Innovation** Translating world-leading science and skills for industry, government and the third sector.

**Training & Fellowships** Developing outstanding scientists to become internationally recognised leaders in science, in academia, business, government, the public sector and civil society.

**Capital** Investing in new technologies, equipment, infrastructure, facilities and estates.

**National Capability** Research centres, ships, aircraft, polar stations, data centres, and community facilities
Strategic Research development:
Highlight Topics and Strategic Programme Areas

Ideas

Strategic Programme Advisory Group (SPAG)

Science Board (SB, formerly known as SISB)

NERC Council
Workshop Scope

- **Within scope** – fossil fuel extraction using hydraulic fracturing (e.g. shale, tight formations)
- **Outside scope** – UGC, hydrocarbon processing and transportation etc.
Programme

• Presentations on the state of knowledge in the USA and UK

• Two sessions to capture the key conclusions (end of Thurs and Friday)

• Report for NSF and NERC to summarise

• Timeline 1\textsuperscript{st} Draft November 2015. Submission to NSF and NERC December 11\textsuperscript{th} 2015.
Unconventional Oil and Gas

• No clear definition of unconventional oil and gas and the definition tends to change with time

• Commonly included
  ✓ Tight oil and gas from shale and sandstones
  ✓ Oil sands
  ✓ Oil shale
  ✓ Gas to liquids
  ✓ Coal/coke to liquids

• Our focus – environmental issues uniquely associated with extraction of hydrocarbons from tight formations via permeability enhancement and hydraulic fracturing
The Gas Boom - Barnett Shale

- Newark East Field, Barnett Shale, 1800 Bcf in 2010
- ~15,000 wells
- drilling has slowed because of price & field maturity

Jon Olson, University of Texas
U.S. Crude Oil Production by State

Source: US Energy Information Administration

Jon Olson, University of Texas
U.S. Crude Oil Production

Source: US Energy Information Administration

Jon Olson, University of Texas
US Gas Fields

Top 100 U.S. natural gas fields by reserves

2013 reserve
354 tcf
US Oil Fields

Top 100 U.S. oil fields by reserves

Note: The top 100 largest oil and gas field locations are plotted using latitude/longitude of the approximate center of the field. Dot diameter is relative to its 2013 proved reserves.
Sources: U.S. Energy Information Administration, Form EIA-23L, Annual Survey of Domestic Oil and Gas Proved Reserves. Latitude/Longitude estimated using Drillinginfo software.

2013 reserve
36.5x10^9 BBls
US Oil & Gas Production Future

Figure 1. U.S. domestic crude oil production by source, 1990-2040

- History
- 2011
- Projections

- Tight oil
- Other lower 48 onshore
- Lower 48 offshore
- Alaska

Figure 3. U.S. dry natural gas production by source, 1990-2040

- History
- 2011
- Projections

- Shale gas
- Nonassociated offshore
- Tight gas
- Nonassociated onshore
- Associated with oil
- Coalbed methane

Source: US Energy Information Administration (eia.gov)

Jon Olson, University of Texas
Drilling (and Production) Sensitive to Price

Eagle Ford Region
Oil production

thousand barrels/day


Oil -71 thousand barrels/day month over month

U. S. Energy Information Administration | Drilling Productivity Report
Current response to low oil prices

US CRUDE OIL PRODUCTION

Shale gas resources worldwide
• Poland > 50 wells but geology may not work

• Romania – Chevron 1 well

• Bulgaria – ban in place

• France and Germany – bans in place

• After Poland initial fast progress, the UK is now taking the lead
• 2011 - UK’s first ‘shale gas’ well. Fracking caused 2.3 M earthquake

• Moratorium imposed until mid 2012

• Significant resource estimates within Carboniferous and Jurassic

• New licences announced 2015
2040 Est. Consumption and Production

Price Sensitivity

Figure 15. World petroleum and other liquid fuels consumption by country grouping in three cases, 2010 and 2040 (million barrels per day)

Figure 16. World petroleum and other liquid fuels production in three cases, 2010 and 2040 (million barrels per day)

World Energy Outlook 2014
Status

- Unconventional hydrocarbon production has dramatically changed energy production in the US and could elsewhere.

- Substantial reserves in the US suggest substantial oil and gas production growth for at least the next 25 years.

- World oil and gas production/consumption will rise:
  - Total production apparently resilient to cost but source is not.
  - Economic benefits to non-OPEC countries if cost is high.

- Will environmental consequences limit potential benefits?

- What are the key unknowns and research gaps that must be filled to minimize and mitigate the potential environmental consequences?
Questions/Comments?
Status and Perspective of Hydraulic Fracturing in the U.S.

Gene L. Theodori
Professor - Department of Sociology
U.S. Social Scientific Research

Attitudes

Behaviors
U.S. Social Scientific Research

- Community residents
- Community leaders
- Landowners
- Industry personnel

- Special populations
  - Working poor
  - Elderly
U.S. Social Scientific Research

- National level
- State level
- Regional level / Play
  - Bakken
  - Barnett
  - Eagle Ford
  - Haynesville
  - Marcellus
  - New Albany
  - Tuscaloosa Marine
  - Uintah Basin
U.S. Social Scientific Research

Attitudes
• Perceptions of the O&G industry
  • Economic & Service-related
  • Social & Environmental
Attitudes

- Perceptions of the O&G industry compared to other sectors of the energy industry
Attitudes
• Perceptions of hydraulic fracturing
U.S. Social Scientific Research

Attitudes
• Perceptions of risks and opportunities
Attitudes
• Trust in certain groups/organizations
Attitudes

• Perceptions of desalinated produced water
Attitudes

- Perceptions of the management, disposal, and reuse of frac flowback
Behaviors
• Engagement in support and opposition activities
Other

- Crime and development
- Set back distances
- Social representations
- Newspaper coverage
- Labor market dynamics
- Communication issues
1. Perception is a key factor in explaining:

   a. attitudes toward, and
   b. actions taken – either in support of or opposition to –

   the development of oil and gas.
2. **Transparent communication between/among all stakeholders is paramount**

   a) Potentially positive aspects and negative consequences

   b) Industry – share more information about shale gas technologies with government and regulatory officials and the general citizenry
Take Aways

3. Probability of risks exists
   (Jacquet 2014)

- Of rapid industrialization (boom and bust)
- Of uneven distribution of cost and benefit
- Of community conflict and ‘corrosive communities’
- Of community stigma
- Of social-psychological stress
4. Trust / distrust

- Trusted the most
- Trusted the least
5. Encourage the creation / advancement of transdisciplinary research and outreach educational programs to address all phases of shale gas development
1. Why?
   - Perceptions
   - Trust
   - Potential safe uses of produced water
2. Boom and bust cycles
   • Shifts in local economies
   • Migration issues
   • Infrastructure issues
   • Community/social services
3. Wealth

- Individual
- Community
4. Relationships between social-psychological disruption and health outcomes
   (Jacquet 2014)
What Next?

5. Studies of resource-based communities vs. studies in resource-based communities
Whole systems approach to unconventional hydrocarbons in the energy system: UK status & perspective

Matthew Agarwala (UEA, Exeter, LSE)
Nov 4th 2015
NERC & NSF workshop, Washington D.C
Systems thinking

£625 Million
Whole System?
Energy landscape

Environmental

Physical, natural & biological

Socioeconomic
A working definition of whole systems energy research aims at a better understanding of the energy landscape incorporating environmental, socio-economic, physical, natural and biological systems at all spatial and temporal scales. It addresses complexities, interactions and interdependencies within the landscape and with other systems. Whole-systems energy research necessarily draws upon a wide range of disciplines and methodologies.
Large number of highly relevant publications

http://www.ukerc.ac.uk/
Whole Systems Energy Modelling Consortium

- Build & link energy UK models
- Provide UK strategic energy modelling
- 4 year EPSRC funding
- Focus on: technology, behaviour, infrastructure, resources
Five year grant (£2.2m) awarded to a consortium of six institutions led by UEA. (PI: Andrew Lovett)
The Challenges

Decarbonising the UK Energy System

Incorporating Natural Capital and Ecosystem Services into Decision Making

Global Context


Energy Futures

Committee on Climate Change scenarios for future power generation.
Programme Objectives

Aim: develop conceptual frameworks and modelling tools to integrate UK energy pathways research with valuation of natural capital’.

Four science objectives: characterising the direct and indirect impacts of different decarbonisation pathways on UK and global environments within the context of the energy, land and water nexus.
Systems thinking

From Wikipedia, the free encyclopedia

This article has multiple issues. Please help improve it by:
- This article may be in need of reorganization to complete writing.
- This article includes a list of references, but its sources need verification.

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Edit this page.
Public engagement: experience in the UK

Rob Ward
Director of Groundwater Science
British Geological Survey
Background

- BGS initiated national baseline monitoring in 2013 (EA and Defra support)
- Consensus on importance of baseline monitoring
- After moratorium (earthquakes) planning applications submitted (2 areas)
- BGS-led consortium initiated wider programme of baseline monitoring in the two areas
- Intensive activity in areas/communities that are extremely sensitivity
- Community support/acceptance essential for success
The Challenge!
Our strategy

TO BE:

• Proactive
• Reactive
• Open and transparent
Proactive

- Project proposal and FAQs
- Press release and public briefings – different stages
- Local authority briefing/meeting/discussion
- Community meetings (Parish Council/MP Question Time) – different reactions!
- Public debates, conferences etc
- Training of field staff, advertising and corporate branding
Community feedback

• Some key community concerns/messages:

  • “We are part of an experiment that we have no control over, or can opt out of”
  • “We feel like guinea pigs”
  • “No one is listening”
  • “Everyone tells us something different, what should we believe”
Reactive

- Enquiries (telephone and email):
  - Public, industry, media, academia
- Anticipate: get information out in an understandable form – open access
- Information requests:
  - FOI/EIR: formal requests to disclose information
- Complaints:
  - Personal contact critical
- Avoidance of confrontation
Key lessons

• Early community engagement AND continued engagement

• Planning activities carefully, and in consultation
• Different approaches may be needed for different areas/groups
• Keep information up-to-date, fresh and understandable
• Respond rapidly to issues and enquiries
• Personal approach is best

• Don’t be surprised by anything and think before you act
Thank you

www.bgs.ac.uk/research/groundwater
Contours of the UK Shale Gas Debate

Professor Mike Bradshaw

Joint US-UK Workshop on Improving Understanding of Potential Environmental Impacts Associated with Unconventional Hydrocarbons
Strong political support from central government, so why so little progress?

"A key part of our long-term economic plan to secure Britain's future is to back businesses with better infrastructure....."That's why we're going all out for shale. It will mean more jobs and opportunities for people, and economic security for our country".

Prime Minister David Cameron
January 2014

“Shale gas can create a bridge while we develop renewable energy, improve energy efficiency and build new nuclear capacity....The Government therefore considers that there is a clear need to seize the opportunity now to explore and test our shale potential.”

Amber Judd, Secretary of State for Energy and Climate Change, September 2015.
Sufficient gas supplies but uncertainty on the source

Zero or 32 bcm!

Future Energy Scenarios 2014
Shale gas extraction in the UK: a review of hydraulic fracturing
June 2012

Policy recommendations for a robust regulatory framework for the shale gas industry in the UK

The Economic Impact on UK Energy Policy of Shale Gas and Oil

Are we fit to frack?
Policy recommendations for a robust regulatory framework for the shale gas industry in the UK

Potential Greenhouse Gas Emissions Associated with Shale Gas Extraction and Use

Getting ready for UK shale gas
Supply chain and skills requirements and opportunities
April 2014

Task Force on Shale Gas
Assessing the Impact of Shale Gas on Climate Change

wbs.ac.uk
Contours of the Shale Gas Debate in the UK

Arguments for...

• It will improve the UK’s energy security by reducing the level of gas import dependence.
• It will generate tax revenue and improve the UK’s balance of payments.
• It will result in lower energy bills.
• It will attract new investment and create new jobs.
• It will promote local (community payments) and regional economic development (Sovereign Wealth Fund and Northern Powerhouse).
• It will make a positive contribution to decarbonisation and the UK’s climate change policy.
• The regulatory regime is fit for purpose and will minimise the risks to the environment and health and safety.

Arguments against...

• Shale gas (methane) as a hydrocarbon contributes to climate change.
• The problem of fugitive emissions reduces its decarbonising benefit.
• Investment in shale gas may reduce investment in renewables and should not receive tax breaks.
• It will not energy reduce energy bills or improve energy security.
• There is a risk of induced seismicity.
• There is a risk of ground water pollution and it will place additional stress on water resources and water treatment.
• There are significant negative local impacts in relation to air, noise and light pollution and traffic congestions.
• It will have a negative impact on the local economy.
• Community payments amount to bribes and create of conflict of interest for County Councils.
• The regulatory regime is inadequate and there is insufficient regulatory capacity.
Shale Gas Regulatory Regime in England (Exploration)

**Oil and Gas Authority:** award of exclusive Petroleum Exploration & Development Licence (PEDL) after open competition

**Oil and Gas Authority:** online well application for <96 hr testing

**Local Council:** Planning Permission

**Environment Agency:** Statutory consultee

**Health and Safety Executive:**
- 21 day notification
- Well integrity

**Environment Agency**
- 21 day notification
- Environmental permits

**Environment Agency** checks with Health and Safety Executive /Environment Agency:
- Issues well consent
- Issues consent to hydraulically fracture (Infrastructure Act 2015)

**Oil and Gas Authority:** 90-day extended well test (EWT), if required, setting limit on hydrocarbons produced, vented or flared

Exploration Well

Source: Tony Grayling, Environment Agency
Should shale gas extraction in the UK be allowed?

PUBLIC PERCEPTION OF SHALE GAS EXTRACTION IN THE UK: HAS BALCOMBE BOTTOMED OUT? Sarah O’Hara, Mathew Humphrey, Jessica Andersson, Rusi Jaspal, Brigitte Nerlich and Wil Knight University of Nottingham, (2015)
A Social Licence to Frack?

“The social licence to operate is the proposition that, even if fully compliant with laws and regulations, activities that are particularly intrusive or perceived to carry significant risk can be vetoed by a hostile public through campaigns, legal actions, demonstrations or other democratic pressures. Such industries must negotiate a ‘Social Licence’ with their community to conduct their business.”

The European Academies Science Advisory Council (2014)

“Public acceptance of large-scale shale gas development will not be gained through industry claims of technological prowess or through government assurances that environmental effects are acceptable. It will be gained by transparent and credible monitoring of the environmental impacts.”

Council of Canadian Academies (2014)
Hydraulic Fracturing and Seismicity in the US

Dr. Jon Olson
Chair and Professor
Department of Petroleum and Geosystems Engineering
The University of Texas at Austin

Washington, DC, November 5, 2015
Railroad Commission says injection wells not linked to Azle earthquakes

- State hearing examiners found lack of evidence to link the wells to earthquakes

- A study by SMU scientists linked the earthquakes near Fort Worth to oil and gas activity

- Flurry of earthquakes convinced lawmakers to fund a broader study
Natural and Man-made Factors Promoting Seismicity

- lake level change
- excess aquifer production
- hydraulic fracturing
- oil, gas & water production
- wastewater injection
- natural tectonics

Hornbach et al. 2015
Mid-Continent Quakes > M3.0

Oklahoma increase mostly likely related to conventional, high water-cut production made possible by high oil prices from USGS NEIC database.
Quakes > M3.0: Texas and Ohio

from USGS NEIC database
North Texas Quake Data, M\geq 2.0

The diameter of the symbol indicates the relative energy of each earthquake, or \(10^{1.5M}\), where M is the Richter magnitude.

- M2.9 quake
- M3.3 quake
- M4.1 quake

from USGS NEIC database
Cumulative water injection into Fort Worth Basin

<table>
<thead>
<tr>
<th>County</th>
<th>Total Inj (BBLs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denton</td>
<td>998,125.93</td>
</tr>
<tr>
<td>Ellis</td>
<td>2,056.13</td>
</tr>
<tr>
<td>Erath</td>
<td>193,115.87</td>
</tr>
<tr>
<td>Hill</td>
<td>410,849.47</td>
</tr>
<tr>
<td>Jack</td>
<td>7,205,744.37</td>
</tr>
<tr>
<td>Johnson</td>
<td>20,156,119.50</td>
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<tr>
<td>Palo Pinto</td>
<td>2,220,136.37</td>
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<tr>
<td>Parker</td>
<td>1,028,496,731.00</td>
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<tr>
<td>Somervell</td>
<td>1,896,367.13</td>
</tr>
<tr>
<td>Tarrant</td>
<td>5,319,323.17</td>
</tr>
<tr>
<td>Wise</td>
<td>5,074,117.03</td>
</tr>
</tbody>
</table>

from Texas Railroad Commission
Azle, TX: Map and X-Section

Hornbach et al. 2015
Azle, TX: Flow modeling and quake timing

Hornbach et al. 2015
Forth Worth Basin

- model 374 water injectors in the Ordovician Ellenburger Dolomite
- 10 year history
- 9 layer finite difference flow model (CMG)

from Texas Railroad Commission
Pressure change maps - Top of Ellenburger

Gono et al., ARMA 15-00419

Jan 2014
Ft Worth Basin: Injection Well Pressures

- Target formation is the Ellenburger Dolomite
- Many wells show high pressures (>0.6 psi/ft)
- Can induce seismicity below frac gradient
- Injection “weakens” fault by reducing effective normal stress

Modified from Ficker (2012)
Ohio Induced Quakes

• M5.0 in 1986, possibly from injection well near Cleveland (Ahmad and Smith, 1988)

• M4.0 in 2011 near Youngstown related to injection (Kim, 2013)
  – completed in Mt. Simon ss AND Precambrian
  – implies ready access to basement faults
  – high rate, high pressure well
Generalized Geology and Profile of a Utica Shale Well Prototype in East Central Ohio

**Injection Zones**
- Approximate base of potable groundwater
  - Black Hand Member ("Big Injun")
  - Berea Sandstone
  - Bedford Shale/Ohio Shale/Olentangy Shale
  - Marcellus Shale
  - Onondaga Limestone
  - Oswego Sandstone
  - Bass Islands/Salina Group
  - Lockport Dolomite
  - "Clinton" sandstone
  - Queenston Shale/Cincinnati group
- Utica Shale
- Trenton Limestone/Black River Group
- Beekmantown dolomite
- Rose Run sandstone
- Copper Ridge dolomite/Conasauga Group
- basal sandstone

**Production Zones**
- "Big Lime"
- Interbedded sandstone, siltstone, shale, coal, and limestone
- Interbedded salt, anhydrite, dolomite, and shale
- Sand and Gravel
- Sandstone
- Limestone
- Dolomite
- Precambrian

**Potential casing set points**
- Typical water well depth (~100 ft)
Typical Completion

- injection into basal Cambrian ss (drilled into pC)
- surface and production casing cemented to surface
- max allowed pressure 1360 psi
- perforated from 5900-7075 ft
Baranoski, 2013

Datum = sea level  Vertical exaggeration = 50X
Diagram based on interpretation approximately along COCORP OH-1 and OH-2 seismic lines
NRC 2013 Induced Seismicity Report

- basic processes are well understood, but prediction is elusive
- hydraulic fracturing as currently practiced “does not pose a high risk for inducing felt seismic events”
- processes that balance injection and withdrawal thought to be much lower risk
- depletion or continuous injection (wastewater) “pose some risk” (very few events associated with ~30,000 class II wells in US)
- “CCS … may have potential for inducing larger seismic events”

National Research Council, 2013, “Induced Seismicity Potential in Energy Technologies”
Wastewater Injection and Seismicity

- high volume injection wells (100,000’s bbls/month)
- inject deep, near basement or in basement
- need large pre-existing fault (often unknown prior to event)
- variable time lag between injection and quake
- recent activity attributed to primarily to unconventionals, BUT in Oklahoma, produced water from conventional play (high water cut)
Scale of Operations

Hydraulic Fracturing

- 50 bbl/minute = 75,000 bbl/day = 11,450 m³/day
- duration ~ hours
- total injected
  - < 10,000 bbls = 1,600 m³/stage
  - ~100,000 bbls / well
- immediately flowed back, reducing pressure

Wastewater Injection

- 2 bbl/minute = 3,000 bbl/day = 460 m³/day
- duration ~ decades
- total injected ~ million bbls/yr
- continuous/intermittent injection, always positive pressure
Impact of Hydraulic Fracture Job Parameters on Seismicity (Warpinski et al., 2012)
Knowledge Gaps?

• subsurface is poorly characterized (even with 1 million+ holes in the US)
• permeability of faults, natural fractures and basement poorly understood
• sparse monitoring of events < M3
• why so few quakes in some areas, from hydraulic fracturing
• ability to predict time lag
• key controls— rate, pressure, volume, gradients, ???
• how big can you induce?
• what are the ground motions and damage?
TexNet: Seismic Monitoring & Research

• monitor seismicity across Texas ≥M2.0
  – 22 new permanent stations
  – 36 portable stations

• broad research program
  – risk/damage assessment
  – geomechanics
  – reservoir engineering
  – public perception/acceptance

• funding
  – Texas legislature allocation
  – industry JIP
Success requires manpower: US Petroleum Engineering Students

~10,000 more BS PE’s in 10 years
Hydraulic fracturing…..

• is NOT like shattering glass
• is NOT explosive
• is NOT uncontrolled failure

• fractures cannot grow faster than pumps can deliver the fluid
• a “typical” frac job might last from 15 minutes to several hours
• fractures stop growing when the pumps are stopped
• hydraulic fractures generate MICRO-seismicity (earthquakes of magnitude $\text{magnitude minus 2}$ – magnitude $\text{magnitude plus 3}$ is minimum to be felt by humans – 10,000 times greater energy than hydraulic fracturing)
Components of a frac job

- Fluid
- Sand
- Blender
- Control van
- Wellhead
- Pumps
Induced Seismicity
How big can they get?

- induced quakes should be $\leq$ natural magnitudes (Frohlich, 2012)
Hydraulic fracturing and seismicity in UK

Michael Kendall
University of Bristol
Induced vs Naturally occurring seismicity

- **Natural** seismicity:
  - Tectonic earthquakes that occur coincidentally with anthropogenic activities

- **Triggered** seismicity:
  - Causative activity accounts for small fracture of stress change associated with earthquakes
  - Pre-existing tectonic stress plays primary role

- **Induced** seismicity:
  - Causative activity accounts for most of the stress change or energy to produce earthquakes

(from McGarr, 1991)
Seismicity in the UK

- Largest $M_L$ 6.1: 07/06 1931, Dogger Bank, North Sea
- Other large events include those in the Irish Sea, Wales, ...
- 10 fatalities, most due to collapse of buildings
- Some risk of tsunamis
Induced Seismicity in the UK

- Geothermal
- Coal
- Radioactive waste (none yet)
- Wind farms (seismic noise).
- N.B.: No waste water injection in the UK
New Ollerton earthquakes

- >50 events recorded in 6 months since Dec 2013
- Largest events $M_L1.7$
- Area of active coal mining
New Ollerton earthquakes

- >50 events recorded since Dec 2013
- Largest events $M_L 1.7$
- Area of active coal mining
Shale gas - Preese Hall, Lancashire, UK
April 2011, $M_L$ 2.3 event shortly after Cuadrilla sources hydraulically fractured a well at its Preese Hall site.

Induced events $-2.0 < M_L < 2.3$

Strike-slip events on tectically stressed fault hydraulic fracturing currently suspended.
Written Ministerial Statement by Rt. Hon. Edward Davey: Exploration for shale gas

Operators will first be required to review the available information on faults in the area of the proposed well to **minimise the risk of activating any fault** by fracking, and...

... required to **monitor background seismicity** before operations commence.

*Real time seismic monitoring* will also continue during operations, with these subject to a **“traffic-light”** regime, so that operations can be quickly paused and data reviewed if unusual levels of seismic activity is observed. Real-time recording of earthquakes during and for 24 hours after each stage of the frac will be analysed to look for abnormal induced events amidst the normal background seismicity.

*Operators will also be required to monitor the growth in height of the frac* away from the borehole. This will allow the operator to evaluate the effectiveness of the frac, but also ensure that the actual fracture is conforming to its design, and that it remains contained and far away from any aquifers.
EU Commission Recommendation

Member States should ensure that operators:

(d) carry out the high-volume fracturing process in a controlled manner and with appropriate pressure management with the objective to contain fractures within the reservoir and to avoid induced seismicity

Minimum principles for the exploration and production of hydrocarbons (such as shale using high-volume hydraulic fracturing – January, 2014
Traffic light system

Traffic light monitoring systems should be implemented and data fed back to well injection operations so that action can be taken to mitigate any induced seismicity.”

- Green. Injection proceeds as planned.
- Amber. Injection proceeds with caution, possibly at reduced rates. Monitoring is intensified.
- Red. Injection is suspended immediately.

from Shale gas extraction in the UK: a review of hydraulic fracturing, Issued: June 2012 DES2597
The Royal Society and The Royal Academy of Engineering 2012
Traffic light system

UK versus Canada
UK Seismic Network

Combination of BB (red) and SP (black) stations
Real time monitoring
Nominal detection level of $M_L$ 2.0
Over 1000 naturally occurring event of $M_L > 0.5$ every year.
Densification of UK Seismic Network - UKArray

- Collaborations between BGS, Bristol and Liverpool
- Government interests: DECC, BIS, EA
- In need of funding
- Numerous independent projects (Igas, 3rd energy, ...)

Transportable Array
- Phase 1
- Phase 2
- Phase 3
- Phase 4
- Phase 5
- Permanent array
- Temporary Network
Vale of Pickering Monitoring

- DECC funded project
- Integrated environmental baseline studies in the vicinity of proposed shale gas exploration and production
- Network of seismic sensors to monitor background seismic activity
- Continuous data available in real time
Looking forward: questions and issues

- Operator versus regulator needs – Induced-seismicity as a function of space and time.
- Operators need a clear set of guidelines/rules.
- How many stations are needed?
- Best array design: surface, shallow borehole, borehole
- How best to calculate magnitude: M_w, M_L or perhaps even PGA
- Traffic light system – M_w0.5 !; who does the monitoring?
- Can we forecast M_{max}?
- What constitutes baseline monitoring?
- Induced versus naturally occurring seismicity.
- New sensor technology; must be broadband
- Connecting geomechanics, fluid flow and seismicity
- Fault reactivation – when and where does this occur?
- Fracture mapping; seismicity, SRV and fractures.
- Public communication.
Induced-seismicity as a function of space and time.

(Verdon 2013)
How many stations are needed?

e.g., Vale of Pickering Monitoring

- Issues of noise levels
Best array design?
Identifying Faults

- High b-values indicate normal hydraulic fracturing. Low b-values indicate fault-reactivation

\[ \log_{10}N(M) = a - bM \]
Identifying Faults

- High b-values indicate normal hydraulic fracturing. Low b-values indicate fault-reactivation.
- What controls whether a HF stage will re-active a fault?
- Does geomechanical modelling have the answer?
Can we forecast $M_{\text{max}}$? Fracking induced events in Alberta (M4.4 largest)

UK Faults and $>M_{4.0}$ events (naturally occurring)
Controls on $M_{\text{max}}$?

- Cumulative moment release is proportional to volume change:
- Dependent on “Seismic Efficiency”: $\Sigma M_o/G\Delta V$
- Dependent on b-value
Controls on $M_{\text{max}}$?

Hydraulic Fracturing (Cotton Valley)
Microseismic events track the formation of fractures.
Tracking the evolution of fracture networks

- Fractures lead to directional variations in velocities – seismic anisotropy
- Important role of pre-existing fractures
- Important role of stress anisotropy
- Active monitoring before, during and after stages

Baird et al., 2013
Looking forward: questions and issues

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• Fault reactivation – when and where does this occur?
• Fracture mapping; seismicity, SRV and fractures.
• Public communication.
UK public perceptions of shale gas hydraulic fracturing: The role of audience, message and contextual factors on risk perceptions and policy support

Lorraine Whitmarsh a, Nick Nash a, Paul Upham b, Alyson Lloyd c, James P. Verdon d, J.- Michael Kendall d

a School of Psychology, Cardiff University, UK
b Institute for Environmental Communication, Leuphana Universität, Germany & Sustainability Research Institute, University of Leeds, UK
c Department of Geography, University College London, UK
d School of Earth Sciences, University of Bristol, UK

HIGHLIGHTS

- First UK experimental online survey of public perceptions of shale gas fracturing.
- The public is ambivalent about shale gas, but also sees more risks than benefits.
- Demographics, politics and environmental values exert strongest influence on perceptions.
- Impact of shale gas information is greatest on attitudinally ambivalent respondents.
Increased Natural Gas Production and Air Quality

David Allen
Department of Chemical Engineering, and Center for Energy and Environmental Resources
University of Texas at Austin
Air Pollutant Emissions associated with Shale Gas production

– Emissions of ozone (smog) precursors
  • Emissions from trucks and other mobile sources servicing sites; from compressors and other drilling and gas processing equipment; fugitive losses of natural gas and natural gas liquids

– Air toxics
  • Benzene from evaporation of natural gas liquids has been an area of concern; chlorinated organics are an emerging concern

– Greenhouse gases
  • New federal reporting rules require estimates of greenhouse gas emissions from oil and gas production and new emission controls
Challenges in estimating emissions

Case of Barnett Shale:
>10,000 wells
Both dry gas and wet gas
Rapidly evolving

- Many potential sources, geographically distributed, temporal variability
- Emissions can depend strongly on equipment type, operating practices, nature of gas being extracted
Multiple approaches for measurement (bottom-up and top-down)

- Direct measurements of sources
- Fixed ground measurement network
- Mobile ground monitoring
- Aircraft monitoring
- Satellite measurements
- Different approaches provide complementary information
Methane from natural gas production:
Why methane?
Much of this natural gas is being used in power generation, lowering Power plant CO₂ emissions...

2,200 lb CO₂/MWh
Coal

950 lb CO₂/MWh
Natural Gas
Power plant emissions...aren’t whole story

Source: Adapted from Jaramillo et al., (2007) EST 41, 6290,
Climate implications of methane

POUND FOR POUND METHANE TRAPS $84x$ MORE HEAT OVER 20 YEARS
ESTIMATES (prior to 2012, no measurements) of volume of gas released during well completion

**Figure 3:** Published estimates of gas volumes released during well completion, versus respective references. Formation is shown in brackets where applicable. The Howarth Haynesville data is considered by many to be an outlier.
Multiple approaches for measurement (bottom-up and top-down)

• Direct measurements of sources
• Fixed ground measurement network
• Mobile ground monitoring
• Aircraft monitoring
• Satellite measurements
• Different approaches provide complementary information
What do these studies tell us?

**Bottom-up**
- Emission from some sources are lower than current estimates (e.g., well completion flowbacks), consistent with new regulations
- Emission from some sources are higher than estimates (e.g., pneumatic controllers)
- Regional variability
- Emissions from some sources are dominated by a small number of wells and devices (leaks, pneumatic controllers, well unloadings)
- Uncertainties in activity counts

**Top-down**
- At national and regional levels, emissions from the natural gas sector are under-estimated
- Regional variability

**Research Gaps:**

**Causes of and emissions from super-emitters**
Will substitution of natural gas for coal or petroleum lead to net climate benefits?
EDF Methane Studies By Part of the Natural Gas Value Chain

Production
0.53% (Allen, et al PNAS 2013)
0.42% (Allen, et al PNAS 2013)

Gathering / Processing
0.19% (EPA GHG Inventory 2013)

Transmission / Storage
0.42% (EPA GHG Inventory 2013)

Local Distribution
0.27% (EPA GHG Inventory 2013)

Trucks & Stations
0.57% (EPA GHG Inventory 2013)

TOTAL METHANE EMISSIONS RATE
Well to power plant = 1.14%
Well to user = 1.41%
Well to wheels = 1.98%
Air Pollutant Emissions associated with Shale Gas production

– Emissions of ozone (smog) precursors
  • Emissions from trucks and other mobile sources servicing sites; from compressors and other drilling and gas processing equipment; fugitive losses of natural gas and natural gas liquids

– Air toxics
  • Benzene from evaporation of natural gas liquids has been an area of concern; chlorinated organics are an emerging concern

– Greenhouse gases
  • New federal reporting rules require estimates of greenhouse gas emissions from oil and gas production and new emission controls
EPA tightening the federal clean air standard for ozone

Current

Possible new

Areas in dark blue represent parts of the country that could be in violation of the ozone standard if it is set at 70 ppb.
To form ozone, need both VOCs and NOx; which is in shortest supply varies from place to place

<table>
<thead>
<tr>
<th>VOCs</th>
<th>NOx</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Emitted from both natural and anthropogenic sources</td>
<td>• Emitted almost exclusively from anthropogenic sources</td>
</tr>
<tr>
<td>• Some VOCs are much more reactive (higher ozone forming potential) than others</td>
<td>• Emitted from combustion sources</td>
</tr>
<tr>
<td>• Biogenic (naturally occurring) VOCs are highly reactive</td>
<td>• Differences in reactivity from source to source are relatively minor</td>
</tr>
</tbody>
</table>
Case Study of the Eagle Ford
Quantify the emissions from the Eagle Ford

- While emissions of volatile organic compounds are the largest in quantity, they are relatively unreactive, and in the Eagle Ford occur in a region with high emissions of biogenics.
- Ozone formation in the Eagle Ford is due almost exclusively to NOx.
Where the emissions occur also matters

NOx emissions that impact San Antonio

NOx emissions that impact Austin
What is the magnitude of the impact?

• Magnitude of impact approximately 1 ppb in Austin and San Antonio, depending on day and location

• Changes in ozone concentrations estimated for the eastern United States as a result of the Ozone Transport Rule, which would have been a major emission reduction program for the electric power sector was 0.09 ppb (RIA)
But emissions from gas production... aren’t the whole story

Electricity and Natural Gas in Texas

% Growth Since 2010
(Texas Railroad Commission)
Effect on Electricity Generation

Average Daily Generation over Episode

- Coal
- Natural Gas

Natural Gas Price ($/MMBTU)
7.74

MWh
- < 5,500
- 5,500 to 13,000
- 15,000 to 21,000
- 21,000 to 29,000
- 29,000 to 46,000
- > 46,000
Effect on Electricity Generation

Average Daily Generation over Episode

- Coal
- Natural Gas

Natural Gas Price ($/MMBTU)

- 3.87
Effect on Electricity Generation

Average Daily Generation over Episode

- Coal
- Natural Gas

Natural Gas Price
($/MMBTU)

2.88
Effect on Electricity Generation

Average Daily Generation over Episode

- Coal
- Natural Gas

Natural Gas Price
($/MMBTU)

1.89
Changes in electricity generation lead to decreases in ozone production

Decreases in ozone as natural gas use increases

Increases in ozone as natural gas production increases
Summary for photochemical smog precursors

• As a new ozone standard is established, there will be increasing attention on emissions of VOCs and NOx from all sources including oil and gas operations

• The impacts of these emissions depend on where they occur and the composition of the atmosphere

• Net impacts are complex and will vary across the state and even within a single play

• **Research gap:** Understanding behavior of entire supply chain; role of snow cover
Air Pollutant Emissions associated with Shale Gas production

– Emissions of ozone (smog) precursors
  • Emissions from trucks and other mobile sources servicing sites; from compressors and other drilling and gas processing equipment; fugitive losses of natural gas and natural gas liquids

– Air toxics (Research gap: Identifying relevant air toxics)
  • Benzene from evaporation of natural gas liquids has been an area of concern; chlorinated organics are an emerging concern

– Greenhouse gases
  • New federal reporting rules require estimates of greenhouse gas emissions from oil and gas production and new emission controls
Acknowledgements

• Funding for the project was provided by the National Science Foundation under the EFRI Program (Grant Number 0835414).
• Texas Advanced Computing Center (TACC) for time on Ranger
Citations: Greenhouse gases


Citations: Regional Air Quality


UK Perspectives on air quality, greenhouse gas emissions and their mitigation

Grant Allen, University of Manchester
grant.allen@manchester.ac.uk
Emissions science in the UK: Scope

Climate change (global)
- Greenhouse gases – direct and “indirect” fugitive emissions
- Oxidative capacity of the atmosphere

Air Quality (local and regional)
- Primary and secondary pollutants
- Regional/global background and transport pathways

What we’re doing in the UK
- NERC MAMM aircraft campaign (Arctic bio/anthro GHGs)
- NERC GAUGE project (UK GHG emissions)
- NCAS Oil & Gas airborne surveys
- DEFRA AQ network (surface stations)
- DECC Tall Tower network (eddy covariance)
- BGS-led baseline monitoring project
Unconventional fugitive emissions

Not just GHGs
- ~30% of shale gases are NMHCs and VOCs (varies with geology)
- Potentially significant impacts on local air quality, health impacts

Lab results from Bowland shale, UK:

Table 2. Total NMHCs Per Unit Mass of Shale Released over a Period of 110 min after Crushing of the Shale Sample under Different Sampling Conditions

<table>
<thead>
<tr>
<th>m/z</th>
<th>hot/dry (sample C2)</th>
<th>hot/humid (sample B1)</th>
<th>cold/dry (sample D1)</th>
<th>cold/humid (sample D2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>83</td>
<td>451914</td>
<td>151970</td>
<td>43670</td>
<td>10698</td>
</tr>
<tr>
<td>85</td>
<td>398684</td>
<td>121474</td>
<td>28515</td>
<td>5912</td>
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<tr>
<td>97</td>
<td>515792</td>
<td>186054</td>
<td>63555</td>
<td>25678</td>
</tr>
<tr>
<td>99</td>
<td>515528</td>
<td>165175</td>
<td>41565</td>
<td>25848</td>
</tr>
<tr>
<td>107</td>
<td>62.4</td>
<td>25.2</td>
<td>9.1</td>
<td>4.1</td>
</tr>
<tr>
<td>121</td>
<td>113.5</td>
<td>39.9</td>
<td>9.3</td>
<td>4.6</td>
</tr>
<tr>
<td>133</td>
<td>1.6</td>
<td>0.7</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>135</td>
<td>15.9</td>
<td>6.7</td>
<td>1.3</td>
<td>0.6</td>
</tr>
<tr>
<td>137</td>
<td>7953</td>
<td>1774</td>
<td>832</td>
<td>171</td>
</tr>
</tbody>
</table>

The shale samples were cylindrical cores (C2, B1, D1, and D2; see Table 1) with a mass of ~127 g before crushing. Units are ppb (nmol/mol) of gas released per gram of rock.

Table c/o Sommariva et al., 2014 - Env. Sci. Tech., 2014, 48, 8891–8896
Local / regional air quality concerns identified in US

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Source</th>
<th>Air quality impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMVOCs</td>
<td>Fugitive emissions during drilling, extraction and transport</td>
<td>Local health impacts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Local and regional ozone production</td>
</tr>
<tr>
<td>Nitrogen oxides (NOx)</td>
<td>Gas processing equipment, mobile machinery and flaring</td>
<td>Local health impacts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Local and regional ozone production</td>
</tr>
<tr>
<td>Ozone</td>
<td>Secondary production</td>
<td>Health impacts</td>
</tr>
<tr>
<td>Sulphur compounds</td>
<td>Fugitive emissions</td>
<td>Health impacts</td>
</tr>
<tr>
<td>PM</td>
<td>Mobile machinery, flaring</td>
<td>Health impacts</td>
</tr>
</tbody>
</table>

Propane mixing ratios in the Uintah basin, UT, compared with several US urban areas.

Contact: (pete.edwards@ncas.ac.uk)
Impacts depend on many factors:

- Industry practice
- Hydrocarbon composition
- Meteorology
- Background air composition

Role of industry practice on well pad NMVOC emissions

Significant Ozone pollution linked to emissions from unconventional hydrocarbon extraction

Air quality impacts will not directly translate from US to UK due to significant differences in factors such as meteorology, population density, legislation, etc.

Contact: pete.edwards@ncas.ac.uk
UK Approaches to GHG and AQ baseline monitoring

Continuous, long-term, on-site measurement – locally representative climatology
UK Approaches to local source/impact apportionment

- Polar bivariate plots conditioned by wind speed and wind direction illustrate potential source regions for the central sampling location.

- In this case, the analysis highlights a nearby working farm...
Diffuse emissions: A problem of scales

**The Problem:** Processes/modelling/understanding at small (e.g. urban) scales not easily extrapolated to large (global) scales.

**Solutions:** Airborne, remote sensing, sensor networks.

**Shorter-term but intensive campaigns** (e.g. mobile surveys – Fred Worral, Durham)
The FAAM Aircraft
FAAM Measurements

- **In situ**
  - $\text{CH}_4$, $\text{CO}_2$, $\text{N}_2\text{O}$
    (Aerodyne QCL, LGR FGGA)
  - CO, $\text{O}_3$, NO$_x$
  - Dropsondes (T, p, q, winds)
  - VOCs, NMHCs, $d_{13}\text{C}(\text{CH}_4)$
- **Whole Air Sample (WAS) system**
  - 64 x 3 litre steel canisters
  - GCxGC: $C_6-C_{13}$ NMHC, oxygenated VOCs
  - Continuous flow GC - Trace gases and $\text{CH}_4 \delta^{13}\text{C}$
- **Remote sensing**
  - Nadir open-path infrared spectroscopy (FTIR)
  - Vertical profiles of $\text{CH}_4$, $\text{N}_2\text{O}$, NOx, O3 etc
Greenhouse gAs Uk and Global Emissions (GAUGE): Quantifying UK anthropogenic GHG emissions

Inter-calibrated atmospheric GHG measurements

Cutting-edge models of atmospheric transport

Estimating posterior emissions by combining measurements and models

Inputs: 1) Measurements and uncertainty and 2) prior emissions uncertainty

Output: Posterior emission estimates and uncertainty

Facilitating better decisions: ensemble of emissions estimates provide uncertainty
Flux Strategies – mass balancing

\[ \text{Flux} = \int_{0}^{B} \int_{A}^{B} (S_{ij} - S_{0}) \cdot n_{ij} \cdot U_{ij} \cdot dx \cdot dz \]

- As per Petron, Wofsy, Kort, and others….
Flight B724 – 30 July 2012

Upwind

Downwind

See O’Shea, Allen et al., Greenhouse has emissions from London during summer 2012, 2014, ACP.
B906/907 (May 2015): Upwind and downwind flights of the UK mainland show net methane enhancement (biogenic + anthropogenic emissions) and net CO$_2$ depletion downwind (biospheric uptake > anthropogenic emissions).

Map shows NAME surface source footprint for downwind flight.
First UAV GHG survey measurements

Landfills as analogue to plant emissions
Nadir FTIR remote sensing with the ARIES instrument on FAAM yields vertical profiles/partial columns that can sense boundary layer sources and additional spatial sampling to mass balancing – Mead et al., in preparation.

Methane and other greenhouse gases in the Arctic - measurements, process studies and modelling (MAMM): Overview

G Allen1 and MAMM team
FAAM Arctic Measurement: MAMM

July 2012
6 flights

August 2013
9 flights

September 2013
7 flights
North Sea oil and gas surveys (MAMM)

- **Summer 2012**
  - B721: Kiruna-Cranfield (23/7/12)

- **Summer 2013**
  - B801: Transit back to Aberdeen (19/8/13)
  - B802: N Sea oil and gas platforms

- **Autumn 2013**
  - B808: Transit back to Aberdeen (23/9/13)
  - B809: N Sea oil and gas platforms

- **Summer 2014**
  - B860: Transit back to Aberdeen (4/7/14)
  - B861: N Sea oil and gas platforms

Methane $\delta^{13}C$: source signatures

- >40 ‰ Gas leak
- -40 to -50 ‰ Mixed
- <50 ‰ Biogenic
Science Questions

• What are the potential AQ impacts in the UK context and how can they be mitigated?
  - MNHC/VOC content of UK shales
  - Primary pollutants and secondary production (UK meteorology)
  - Transport processes and population density

• What are the fugitive emission fluxes from the industry and how can these be mitigated?
  - What technology/sampling is optimal for constraining flux (and flux uncertainty)?
  - How does top-down compare to inventories?
  - Can soil microbiology etc mitigate CH₄ diffuse emission?

• How can local baselines be extrapolated to broader representative footprints?
  - Optimal networks
  - Background and extraneous inputs
Joint US-UK Workshop on Improving Understanding of Potential Environmental Impacts Associated with Unconventional Hydrocarbons

United States Experience with Risks to Water Quality and Availability

Avner Vengosh
Collaborative research on Hydraulic fracturing
A Critical Review of the Risks to Water Resources from Unconventional Shale Gas Development and Hydraulic Fracturing in the United States

Avner Vengosh,*† Robert B. Jackson,‡‡ Nathaniel Warner,§ Thomas H. Darrah,¶‖ and Andrew Kondash†

†Division of Earth and Ocean Sciences, Nicholas School of the Environment, Duke University, Durham, North Carolina 27708, United States
‡School of Earth Sciences, Woods Institute for the Environment, and Precourt Institute for Energy, Stanford University, Stanford, California 94305, United States
§Department of Earth Sciences, Dartmouth College, Hanover, New Hampshire 03755, United States
¶School of Earth Sciences, The Ohio State University, Columbus, Ohio 43210, United States

Supporting Information

ABSTRACT: The rapid rise of shale gas development through horizontal drilling and high volume hydraulic fracturing has expanded the extraction of hydrocarbon resources in the U.S. The rise of shale gas development has triggered an intense public debate regarding the potential environmental and human health effects from hydraulic fracturing. This paper provides a critical review of the potential risks that shale gas operations pose to water resources, with an emphasis on case studies mostly from the U.S. Four potential risks for water resources are identified: (1) the contamination of shallow aquifers with fugitive hydrocarbon gases (i.e., stray gas contamination), which can also potentially lead to the salinization of shallow groundwater through leaking natural gas wells and subsurface flow; (2) the contamination of surface water and shallow groundwater from spills, leaks, and/or the disposal of inadequately treated shale gas wastewater; (3) the accumulation of toxic and radioactive elements in soil or stream sediments near disposal or spill sites; and (4) the overextraction of water resources for high-volume hydraulic fracturing that could induce water shortages or conflicts with other water users, particularly in water-scarse areas. Analysis of published data (through January 2014) reveals evidence for stray gas contamination, surface water impacts in areas of intensive shale gas development, and the accumulation of radium isotopes in some disposal and spill sites. The direct contamination of shallow groundwater from hydraulic fracturing fluids and deep formation waters by hydraulic fracturing itself, however, remains controversial.
Major risks for water contamination associated with shale gas development and hydraulic fracturing

Water footprint
- Water exploitation in water-scare areas;
- Long-term impacts on over-exploited aquifers

Groundwater contamination
- Stray gas contamination
- Flow of saline water/hydraulic fracturing fluids

Surface water contamination
- Spills, leaks;
- Disposal of wastewater
- Accumulation of toxic residues, radiation in impacted sites

Vengosh et al. (2014) ES&T, 48, 8334-8348
Major risks for water contamination: implications for the UK

Water footprint
- Water exploitation in water-scare areas;
- Long-term impacts on over-exploited aquifers

Groundwater contamination
- Stray gas contamination
- Flow of saline water/hydraulic fracturing fluids
- Adequate baseline and monitoring program

Surface water contamination
- Spills, leaks;
- Disposal of wastewater
- Accumulation of toxic residues, radiation in impacted sites
- Adequate wastewater management plan

Planning water supply
Pathways of water contamination
Part One: The water footprint of hydraulic fracturing

The risks:

- Water use for hydraulic fracturing could compete with other water uses, particularly in water scarce areas;
- Could water scarcity be a limiting factor for hydraulic fracturing?
- Are arid regions worldwide ready for future hydraulic fracturing?
Water Footprint of Hydraulic Fracturing

Andrew Kondash and Avner Vengosh*

Division of Earth and Ocean Sciences, Nicholas School of the Environment, Duke University, Durham, North Carolina 27708, United States

Supporting Information

ABSTRACT: We evaluated the overall water footprint of hydraulic fracturing of unconventional shale gas and oil throughout the United States based on integrated data from multiple database sources. We show that between 2005 and 2014, unconventional shale gas and oil extraction used 708 billion liters and 232 billion liters of water, respectively. From 2012 to 2014, the annual water use rates were 116 billion liters per year for shale gas and 66 billion liters per year for unconventional oil. Integrated data from 6 to 10 years of operation yielded 803 billion liters of combined flowback and produced water from unconventional shale gas and oil formations. While the hydraulic fracturing revolution has increased water use and wastewater production in the United States, its water use and produced water intensity is lower than other energy extraction methods and represents only a fraction of total industrial water use nationwide.
An assembly of national dataset:

- Data integration from multiple sources;
- A comparison to previous publications
A comparison of water use found in this study and values reported in the literature

### Shale Gas Play

<table>
<thead>
<tr>
<th>Shale Gas Play</th>
<th>FracFocus Median (x10^6 L)</th>
<th>FracFocus Mean (x10^6 L)</th>
<th>Water Use (x10^6 L)</th>
<th>Water Use Chesapeake Energy (x10^6 L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barnett</td>
<td>13.99</td>
<td>14.67</td>
<td>18.93</td>
<td>18.93</td>
</tr>
<tr>
<td>Eagle Ford</td>
<td>13.81</td>
<td>15.90</td>
<td>18.22</td>
<td>18.17</td>
</tr>
<tr>
<td>Fayetteville</td>
<td>20.02</td>
<td>19.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haynesville</td>
<td>19.90</td>
<td>21.18</td>
<td>21.5</td>
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<tr>
<td>Marcellus</td>
<td>16.00</td>
<td>16.04</td>
<td>14.8</td>
<td>21.20</td>
</tr>
<tr>
<td>Niobrara</td>
<td>1.50</td>
<td>2.13</td>
<td></td>
<td>12.49</td>
</tr>
<tr>
<td>Woodford</td>
<td>24.02</td>
<td>24.54</td>
<td>15.20</td>
<td></td>
</tr>
</tbody>
</table>

### Tight Oil Play

<table>
<thead>
<tr>
<th>Tight Oil Play</th>
<th>FracFocus Median (x10^6 L)</th>
<th>FracFocus Mean (x10^6 L)</th>
<th>Total Water Use (x10^6 L)</th>
<th>Water Use Chesapeake Energy (x10^6 L)</th>
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</thead>
<tbody>
<tr>
<td>Bakken</td>
<td>7.50</td>
<td>7.96</td>
<td>8.68</td>
<td>ND SWC (2014)</td>
</tr>
<tr>
<td>Permian</td>
<td>1.52</td>
<td>3.99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>California</td>
<td>0.29</td>
<td>0.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eagle Ford</td>
<td>15.05</td>
<td>16.34</td>
<td>18.22</td>
<td>Scanlon (2014)</td>
</tr>
<tr>
<td>Niobrara</td>
<td>7.08</td>
<td>6.02</td>
<td></td>
<td>12.49</td>
</tr>
<tr>
<td>Woodford</td>
<td>9.35</td>
<td>11.03</td>
<td>15.20</td>
<td>Murray (2013)</td>
</tr>
</tbody>
</table>
Tables of median water use (x10^6 L/Well, x10^6 Gallons/Well), average flowback and produced water (x10^6 L/Well, x10^6 Gal/Well), WUI (L/Gigajoule), and PWI (L/GJ) among the prominent shale gas and tight oil formations

<table>
<thead>
<tr>
<th>Shale Gas Play</th>
<th>FracFocus Median Water Use</th>
<th>FP Water</th>
<th>Water Use Intensity (WUI)</th>
<th>Produced Water Intensity (PWI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barnett</td>
<td>13.98, 3.69</td>
<td>12.40, 3.28</td>
<td>7.17</td>
<td>6.36</td>
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<tr>
<td>Eagle Ford</td>
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<td>25.87, 6.83</td>
<td>5.42</td>
<td>10.16</td>
</tr>
<tr>
<td>Fayetteville</td>
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<td>17.51, 4.63</td>
<td>3.30</td>
<td>2.90</td>
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<tr>
<td>Haynesville</td>
<td>19.90, 5.26</td>
<td>5.20, 1.37</td>
<td>3.12</td>
<td>1.01</td>
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<td>Marcellus</td>
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<td>2.73</td>
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<td>1.50, 0.40</td>
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<tr>
<td>Woodford</td>
<td>24.02, 6.35</td>
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<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Tight Oil Play</th>
<th>FracFocus Median Water Use</th>
<th>FP Water</th>
<th>Water Use Intensity (WUI)</th>
<th>Produced Water Intensity (PWI)</th>
<th>FP Water / Oil Ratio</th>
<th>Water Use / Oil Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bakken</td>
<td>7.50, 1.98</td>
<td>12.25, 3.24</td>
<td>5.00</td>
<td>8.17</td>
<td>0.36</td>
<td>0.22</td>
</tr>
<tr>
<td>Permian</td>
<td>1.52, 0.40</td>
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<td></td>
<td></td>
<td>0.36</td>
<td>0.07</td>
</tr>
<tr>
<td>Monterey-Temblor</td>
<td>0.29, 0.08</td>
<td>14.30, 3.78</td>
<td>1.57</td>
<td>76.43</td>
<td>3.22</td>
<td>0.07</td>
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<td>Eagle Ford</td>
<td>15.05, 3.98</td>
<td>22.75, 6.01</td>
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<td>0.56</td>
<td>0.37</td>
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<td>Niobrara</td>
<td>7.08, 1.87</td>
<td>8.04, 2.12</td>
<td>5.98</td>
<td>6.79</td>
<td>0.44</td>
<td>0.39</td>
</tr>
<tr>
<td>Woodford</td>
<td>9.35, 2.47</td>
<td></td>
<td></td>
<td></td>
<td>8.58</td>
<td>0.89</td>
</tr>
</tbody>
</table>
Since 2005 unconventional shale gas and tight sand oil have used 708 billion liters of water for hydraulic fracturing for shale gas and 232 billion liters for unconventional oil → total of 940 billion liters.

In 2012-2014 water use for hydraulic fracturing was 183 billion liters per year (0.8% of the total annual industrial water use 2.07x10^{13} L per year)

Water intensity of hydraulic fracturing (0.7-9.3 L/GJ) is higher than conventional oil and gas exploration (~0.7 L/GJ), but lower than enhanced oil recovery (120 L/GJ), coal (28.4 L/GJ) and uranium mining (23.8 (L/GJ)

*L/GJ = Liter/Gigajoule*
Water footprint of hydraulic fracturing

Implications to the UK research:

• Multiple data sources is a limiting factor; recommend to establish a national database for water use, wastewater generation, wastewater disposal/management.
• Water use and wastewater information should be provided by the industry as part of the permit process, not volunteer like in the US.
• Data should be transparent and enable local communities to evaluate local risks of water withdrawals and wastewater management.
Part Two: Stray gas contamination

The risks:

• Occurrence of elevated levels of methane and in shallow drinking water wells can pose a potential flammability or explosion hazard to homes near shale gas drilling sites;
• Shut-down of private drinking water wells, need for alternative water resources;
• Houses and property devaluation;
• Methane oxidation – sulfate reduction $\rightarrow$ human health risk from $\text{H}_2\text{S}$ in drinking water wells.
The debate on stray gas contamination

No risk: Methane is always naturally occurring in groundwater, with higher concentrations observed in valleys vs. upland; methane concentrations are best correlated to topographic and hydrogeological factors rather than shale-gas extraction (Molofsky et al., 2013; Segal et al., 2015).

High risk in a subset of wells near shale gas sites: Evidence for stray gas contamination in a subset of wells less than a km from shale gas sites in northeastern PA (Osborn et al., 2011; Jackson et al., 2013; Darrah et al., 2014).
Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing

Stephen G. Osborn1, Avner Vengosh2, Nathaniel R. Warner3, and Robert B. Jackson4

1Center on Global Change, Nicholas School of the Environment, *Division of Earth and Ocean Sciences, Nicholas School of the Environment, and Biology Department, Duke University, Durham, NC 27708

Edited* by William H. Schlesinger, Cary Institute of Ecosystem Studies, Millbrook, NY, and approved April 14, 2011 (received for review January 13, 2011)

Directional drilling and hydraulic-fracturing technologies are dramatically increasing natural-gas extraction. In aquifers overlaying the Marcellus and Utica shale formations of northeastern Pennsylvania and upstate New York, we document systematic evidence for methane contamination of drinking water associated with shale-gas extraction. In active gas-extraction areas (one or more gas wells within 1 km), average and maximum methane concentrations in drinking-water wells increased with proximity to the nearest gas well and were 19.2 and 64 mg CH4 L−1 (n = 26), a potential explosion hazard; in contrast, dissolved methane samples in neighboring nonextraction sites (no gas wells within 1 km) were significantly less negative for active than for nonactive sites (−37 ± 17% and −54 ± 11%, respectively; P < 0.0001). These δ13C-CH4 data, coupled with the ratios of methane-to-higher-chain hydrocarbons, and δ13C-CHOH values, are consistent with deeper thermogenic methane sources such as the Marcellus and Utica shales at the active sites and matched gas geochemistry from gas wells nearby. In contrast, lower-concentration samples from shallow groundwater at nonactive sites had isotopic signatures reflecting a more biogenic or mixed biogenic/thermogenic methane source. We found no evidence for contamination of drinking-water samples with deep saline brines or fracturing fluids. We conclude that greater stewardship, data, and—possibly—regulation are needed to ensure the sustainable future of shale-gas extraction and to improve public confidence in its use.

Increases in natural-gas extraction are being driven by rising energy demands, mandates for cleaner burning fuels, and the economies of energy use (1–5). Directional drilling and hydraulic-fracturing technologies are allowing expanded natural-gas extraction from organic-rich shale in the United States and elsewhere (2, 3). Accompanying the benefits of such extraction (6, 7) are public concerns about drinking-water contamination from drilling and hydraulic fracturing that are ubiquitous but lack a strong scientific foundation. In this paper, we evaluate the potential impacts associated with gas-well drilling and fracturing on shallow groundwater systems of the Catskill and Lackawanna formations that overlie the Marcellus Shale in Pennsylvania and the Genesee Group that overlies the Utica Shale in New York (Figs. 1 and 2 and Fig. S1). Our results show evidence for methane contamination of shallow drinking-water systems in several areas of the region and suggest important environmental risks accompanying shale-gas exploration worldwide.

The drilling of organic-rich shales, typically of Upper Devonian to Ordovician age, in Pennsylvania, New York, and elsewhere in the Appalachian Basin is spreading rapidly, raising concerns for impacts on water resources (8, 9). In Susquehanna County, Pennsylvania alone, approved gas-well permits in the Marcellus formation increased 27-fold from 2007 to 2009 (10).

**Fig. 1.** Map of drilling operations and well-water sampling locations in Pennsylvania and New York. The star represents the location of Binghamton, New York (Inset). A close-up in Susquehanna County, Pennsylvania, showing areas of active (closed circles) or nonactive (open triangles) extraction. A drinking-water well is classified as being in an active extraction area if a gas well is within 1 km (see Methods). Note that drilling has already spread to the area around Brooklyn, Pennsylvania, primarily a nonactive location at the time of our sampling (see inset). The stars in the inset represent the towns of Dimock, Brooklynn, and Montrose, Pennsylvania.

Concerns for impacts to groundwater resources are based on (i) fluid (water and gas) flow and discharge to shallow aquifers due to the high pressure of the injected fracturing fluids in the gas wells (10); (ii) the toxicity and radioactivity of produced water from a mixture of fracturing fluids and deep saline formation waters that may discharge to the environment (11); (iii) the potential explosion and asphyxiation hazard of natural gas; and (iv) the large number of private wells in rural areas that rely on shallow groundwater for household and agricultural use—up to one million wells in Pennsylvania alone—that are typically unregulated and untested (8, 9, 12). In this study, we analyzed ground-water from 68 private water wells from 36- to 190-m deep in


The authors declare no conflict of interest.

*This Direct Submission article had a prearranged editor.

Freedly available online through the PNAS open access option.

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This article contains supporting information online at www.pnas.org/lookup/suppl/ doi:10.1073/pnas.1106621108―4 Supplemental.
Increased stray gas abundance in a subset of drinking water wells near Marcellus shale gas extraction


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Increased stray gas abundance in a subset of drinking water wells near Marcellus shale gas extraction.

Proceedings of National Academy of Sciences, June 24, 2013

Unconventional sources of gas and oil are transforming energy supplies in the United States (1, 2). Horizontal drilling and hydraulic fracturing are driving this transformation, with shale gas and other unconventional sources now yielding more than one-third of all US natural gas supply. In January of 2013, for instance, the daily production of methane (CH₄) in the United States rose to ∼2.3×10⁶ m³, up 8% from the beginning of 2008 (3).

Along with the benefits of rising shale gas extraction, public concerns about the environmental consequences of hydraulic fracturing and horizontal drilling are also growing (4, 5). These concerns include changes in air quality (6), human health effects for workers and people living near well pads (5), induced seismicity (7), and controversy over the greenhouse gas balance (8, 9).

Perhaps the biggest health concern remains the potential for drinking water contamination from fracturing fluids, natural formation waters, and stray gases (4, 10–12). Despite public concerns over possible water contamination, only a few studies have examined drinking water quality related to shale gas extraction (4, 11, 13). Working in the Marcellus region of Pennsylvania, we published peer-reviewed studies of the issue, finding no evidence for increased concentrations of salts, metals, or radioactivity in drinking water wells accompanying shale gas extraction (4, 11). We did find higher methane concentrations and less negative δ¹³C-CH₄ signatures, consistent with a natural gas source, in water for homeowners living <1 km from shale gas wells (4). Here, we present a more extensive dataset for natural gas in shallow water wells in northeastern Pennsylvania, comparing the data with sources of thermogenic methane, biogenically derived methane, and methane found in natural seeps. We present comprehensive analyses for distance to gas wells and ethane and propane concentrations, two hydrocarbons that are not derived from biogenic activity and are associated only with natural seeps. Finally, we use extensive isotopic data e.g., δ¹⁴C-CH₄, δ³¹P-CH₄, δ¹³C-dissolved inorganic carbon (δ¹³C-DIC), and δ⁰H H₂O and helium analysis (He/CH₄) to distinguish among different sources for the gases observed (14–16).

Our study area (Figs. S1 and S2) is within the Appalachian Plateau physiographic province (17, 18) and includes six counties in Pennsylvania (Bradford, Lackawanna, Sullivan, Susquehanna, Wayne, and Wyoming). We sampled 81 new drinking water wells from the three principal aquifers (Alluvium, Catskill, and Lock Haven) (Fig. S1) (11). We combined the data with results from 60 previously sampled wells in Pennsylvania (4) and included a few wells from the Genesee Formation in Otsego County of New York (4). The typical depth of drinking water wells in our study was ∼60–90 m (11). We also sampled a natural methane seep at the Spring State Park in Franklin Forks, Pennsylvania (N41.9197°, W75.8653°, Susquehanna County) to compare with drinking water from homes in our study, some located within a few kilometers of the spring.

Descriptions of the underlying geology, including the Marcellus Formation found 1,500–2,500 m underground, are presented in refs. 4 and 11 and Fig. S2. Previous researchers have characterized the region’s geology and aquifers (19–23). Briefly, the two major bedrock aquifers are the Upper Devonian Catskill Formation, comprised primarily of a delicate clastic wedge gray-green to gray-red sandstone, siltstone, and shale, and the underlying Lock Haven Formation, consisting of interbedded fine-grained sandstone, siltstone, and silty shale (19, 22, 24). These two formations can be as deep as ~1,000 m in the study area and have been exploited elsewhere for oil and gas historically. The sedimentary sequences are gently folded and dip shallowly (1–3°) to the east and south (Fig. S2), creating alternating exposures of synclines and anticlines at the surface (17, 23, 25). Three formations are overlain by the Alluvium aquifer, comprised of unconsolidated glacial till, alluvium sediments, and postglacial deposits found primarily in valley bottoms (20, 22).

**Note:** This article is a PNAS Direct Submission. Freely available online through the PNAS open access option.
Definition of active versus non-active wells:
Private wells located <1km from a shale gas had typically higher methane

(Osborn et al., 2011; PNAS, 108,8172-8176)
Reinforcement of the data:

Presence of ethane and propane in wells <1 km from nearest Gas well → must be derived from thermogenic source (no ethane and propane in biological gas)

(Jackson et al., 2013; PNAS, June 2013)
Methane sources?

A distinction between active wells with a thermogenic isotopic fingerprint and non-active wells with a mixed composition

(Osborn et al., 2011; PNAS, 108, 8172-8176)
Noble gases identify the mechanisms of fugitive gas contamination in drinking-water wells overlying the Marcellus and Barnett Shales

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Edited by Thure C. Cerling, University of Utah, Salt Lake City, UT, and approved August 12, 2014 (received for review November 27, 2013)

Horizontal drilling and hydraulic fracturing have enhanced energy production but raised concerns about drinking-water contamination and other environmental impacts. Identifying the sources and mechanisms of contamination can help improve the environmental and economic sustainability of shale-gas extraction. We analyzed 113 and 20 samples from drinking-water wells overlying the Marcellus and Barnett Shales, respectively, examining hydrocarbon abundance and isotopic compositions (e.g., C2H6/CH4, 813C-CH4) and, providing, to our knowledge, the first comprehensive analyses of noble gases and their isotopes (e.g., 3He, 38Ne, 39Ar) in groundwater near shale-gas wells. We addressed two questions: (i) Are elevated levels of hydrocarbon gases in drinking-water aquifers near gas wells natural or anthropogenic? (ii) If fugitive gas contamination exists, what mechanisms cause it? Against a backdrop of naturally occurring salt- and gas-rich groundwater, we identified eight discrete clusters of fugitive gas contamination, seven in Pennsylvania and one in Texas that showed increased contamination through time. Where fugitive gas contamination occurred, the relative proportions of thermogenic hydrocarbon gas (e.g., C3+H, 3He) were significantly higher (P < 0.01) and the proportions of atmospheric gases (air-saturated water; e.g., N2, Ne, 38Ar) were significantly lower (P < 0.01) relative to background groundwater. Noble gas isotope and hydrocarbon data link four contamination clusters to gas leakage from intermediate-depth strata through failures of annulus cement three to target production gases that seem to implicate faulty production casings, and one to an underground gas well failure. Noble gas data appear to rule out gas contamination by upward migration from depth through overlying geological strata triggered by horizontal drilling or hydraulic fracturing.

Rising demands for domestic energy resources, mandates for cleaner burning fuels, and efforts to reduce greenhouse gas emissions are driving an energy transformation from coal toward hydrocarbon gases produced from unconventional resources (1, 2). Horizontal drilling and hydraulic fracturing have substantially increased hydrocarbon recovery from black shales and other unconventional resources (1, 2) (Fig. S1) to the extent that shale gas now accounts for more than one third of the total natural-gas production in the United States (3).

Public and political support for unconventional energy extraction is tempered by environmental concerns (4, 5), including the potential for compromised drinking-water quality near shale-gas development (6, 7). The presence of elevated methane and aliphatic hydrocarbons (ethane, propane, etc.) in drinking water, for example, remains controversial and requires distinguishing between natural and anthropogenic sources (8–12). Some studies have suggested that shale-gas development results in fugitive gas contamination in a subset of wells near drill sites (6, 7), whereas others have suggested that the distribution of hydrocarbon gases in aquifers overlying the Marcellus Shale is natural and unrelated to shale-gas development (8, 9, 13). This study addresses these critical questions: (i) Are elevated levels of hydrocarbon gas in drinking-water aquifers near gas wells derived from natural or anthropogenic sources? (ii) If fugitive gas contamination exists, what mechanisms cause it?

Previous efforts to resolve these questions identify the genetic fingerprint of hydrocarbon gases using the molecular (e.g., C2H6, heavier aliphatic hydrocarbons) (14) and stable isotopic (e.g., 813C-CH4, 815N-H2O, or 813C-CO2; minus 813C-H2O) (15, 16) compositions of hydrocarbon gases (8–10, 13) (SI Text). These techniques resolve thermogenic and biogenic hydrocarbon contributions and differentiate between hydrocarbon sources of differing thermal maturity (e.g., Middle-Devonian (Marcellus)-produced gases vs. Upper Devonian (UD) gas pockets at intermediate depths). However, microbial activity and oxidation can alter the original geochemical signature (14) and obscure the sources or mechanisms of fluid migration (8, 9).

Noble gas elemental and isotopic tracers constitute an appropriate complement to hydrocarbon geochemistry. Their nonreactive nature (i.e., unaffected by chemical reactions or microbial activity) (14) and well-characterized isotopic compositions in the crust, hydrosphere, and atmosphere (SI Text) make noble gases ideal tracers of crustal fluid processes (14–17). In most aquifers,

**Significance**

Hydrocarbon production from unconventional sources is growing rapidly, accompanied by concerns about drinking-water contamination and other environmental risks. Using noble gas and hydrocarbon tracers, we distinguish natural sources of methane from anthropogenic contamination and evaluate the mechanisms that cause elevated hydrocarbon concentrations in drinking water near natural-gas wells. We document fugitive gases in eight clusters of domestic water wells overlying the Marcellus and Barnett Shales, including declining water quality through time over the Barnett. Gas geochemistry data implicate leaks through annulus cement (four cases), production casings (three cases), and underground well failure (one case) rather than gas migration induced by hydraulic fracturing deep underground. Determining the mechanisms of contamination will improve the safety and economics of shale-gas extraction.


The authors declare no conflict of interest.

This article is a PNAS Direct Submission. Freely available online through the PNAS open access option.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1321071111/DCSupplemental.

www.pnas.org/cgi/doi/10.1073/pnas.1321071111

Proceedings of National Academy of Sciences, September 15, 2014
Noble gas geochemistry: A noble methodology to identify the source of natural gas and mechanism of transport in water

- Noble gas ratios can identify the gas sources (e.g., high He/CH$_4$ ratios) while integrated with traditional stable isotopes of $\delta^{13}$C-CH$_4$ and $\delta^2$H-CH$_4$ and hydrocarbons ratios;

- The different solubility of noble gases provides a tool to distinguish between dissolved gas in water and free gas that derives directly from leaking of shale gas wells → distinction between naturally occurring methane in aquifers and stray gas contamination.

(Darrah et al., 2014; PNAS, Sep 2014)
Identification of fugitive gas migration and contamination

1. Shallow microbial
2. Geologic migration of gas-rich brine
3. Exsolution of “in-situ” gases
4. Annulus-conducted gas
5. Faulty production casing
6. Migration from depth from hydraulic fracturing
7. Leakage from abandoned wells

(Darrah et al., 2014; PNAS)
Stream Measurements Locate Thermogenic Methane Fluxes in Groundwater Discharge in an Area of Shale-Gas Development

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Supporting Information

ABSTRACT: The environmental impacts of shale-gas development on water resources, including methane migration to shallow groundwater, have been difficult to assess. Monitoring around gas wells is generally limited to domestic water-supply wells, which often are not situated along predominant groundwater flow paths. A new concept is tested here: combining stream hydrocarbon and noble-gas measurements with reach mass-balance modeling to estimate thermogenic methane concentrations and fluxes in groundwater discharging to streams and to constrain methane sources. In the Marcellus Formation shale-gas play of northern Pennsylvania (U.S.A.), we sampled methane in 15 streams as a reconnaissance tool to locate methane-laden groundwater discharge: concentrations up to 69 μg L⁻¹ were observed, with four streams ≥5 μg L⁻¹. Geochemical analyses of water from one stream with high methane (Sugar Run, Lycoming County) were consistent with Middle Devonian gases. After sampling was completed, we learned of a state regulator investigation of stray-gas migration from a nearby Marcellus Formation gas well. Modeling indicates a groundwater thermogenic methane flux of about 0.5 kg d⁻¹ discharging into Sugar Run, possibly from this fugitive gas source. Since flow paths often coalesce into gaining streams, stream methane monitoring provides the first watershed-scale method to assess groundwater contamination from shale-gas development.
Evidence of stray gas flow to local streams in PA
Multiple evidence for stray gas contamination

- High methane in wells close to shale gas sites
- Distinctive noble gas geochemistry
- Distinctive hydrocarbon geochemistry and stable carbon isotopes
- Major inorganic chemistry
Stray gas contamination

The bottom lines:

• Integrated geochemical analysis indicates that a subset of drinking water wells near shale gas wells in PA and TX is affected by stray gas contamination while the majority of wells contain naturally occurring methane;
• Data indicate that methane is leaking as free gas from shale gas wells $\rightarrow$ reflects **wells integrity** rather that migration of natural gas from depth.
• No evidence, thus far, for migration of hydraulic fracturing fluids from depths and contamination of drinking water wells.
Stray gas contamination

Implications for the UK:

• Monitoring and baseline studies must include integrated and comprehensive dataset, including inorganic and trace elements, hydrocarbons (methane, ethane, propane), hydrocarbons isotopes ($\delta^{13}$C-CH$_4$), stable and dissolved ions isotopes ($^{87}$Sr/$^{86}$Sr, $\delta^{11}$B), and noble gas geochemistry.

• Research focus on subsurface connectivity and possible migration of fluids and gas between deep, intermediate, and shallow formations in areas of shale gas development.

• Research focus on elucidating the occurrence of naturally occurring hydrocarbons in shallow aquifer systems.
Part Three: Water contamination from hydraulic fracturing fluids

The risks:

- Uncontrolled spills – high frequency in areas of high drilling intensity.
- Contamination of surface water and shallow aquifers from spills and leaks of storage reservoirs
- Disposal of wastewater without adequate treatment – contamination of water resources
- Accumulation of radioactivity in stream sediments and soil – generation of radioactivity legacy.
- Potential of formation of highly carcinogenic disinfection by products in downstream drinking water utilizes.
Injected water
Formation water

Produced water

Gas/oil

Formation water

Typically thousands of meters down
Since 2005 unconventional shale gas and oil have generated 803 billion liters of flowback and produced (FP) water.

The ratio of EP water to unconventional oil is ~0.4, while the ratio of produced water to conventional oil is >3 \(\rightarrow\) less wastewater intensity.

Kondash and Vengosh, 2015
Over a longer time scale of 4 years → the produced water is composed of entirely the formation water.

The geochemical data of flowback and produced waters from the Marcellus shale gas wells indicate that the produced water is composed almost entirely of formation water (brines).

Data source:
What’s in flowback and produced water?

- Man-made chemicals
- Naturally occurring radioactive materials
- Halides (chloride, bromide, iodide)
- Inorganic contaminants (ammonium, barium, strontium)

Halides (chloride, bromide, iodide)
Characterization and Analysis of Liquid Waste from Marcellus Shale Gas Development

Jhii-Shyang Shih, James E. Saires, Shimon C. Anisfeld, Ziyan Chu, Lucija A. Muehlenbachs, and Sheila M. Olmstead

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Flowback (802) □ Produced Water (804)

* Distributions of Flowback and Produced Water are statistically different
+ EC plotted on the same scale as the vertical axis on the left, but units are \( \mu \text{mhos/cm} \)

In the case of oil and grease, only min, 50%, 75% and max were calculated.
TDS (Total Dissolved Solid), EC (Electrical Conductivity), NORMs (Naturally Occurring Radioactive Materials).
Please refer to the secondary vertical axis on the right for NORMs’ units.
Number under each boxplot is the number of samples.
Biocides in Hydraulic Fracturing Fluids: A Critical Review of Their Usage, Mobility, Degradation, and Toxicity

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Supporting Information

ABSTRACT: Biocides are critical components of hydraulic fracturing (“fracking”) fluids used for unconventional shale gas development. Bacteria may cause bioflooding and inhibit gas extraction, produce toxic hydrogen sulfide, and induce corrosion leading to downhole equipment failure. The use of biocides such as glutaraldehyde and quaternary ammonium compounds has spurred a public concern and debate among regulators regarding the impact of inadvertent releases into the environment on ecosystem and human health. This work provides a critical review of the potential fate and toxicity of biocides used in hydraulic fracturing operations. We identified the following physicochemical and toxicological aspects as well as knowledge gaps that should be considered when selecting biocides: (1) uncharged species will dominate in the aqueous phase and be subject to degradation and transport whereas charged species will sorb to soils and be less bioavailable; (2) many biocides are short-lived or degradable through abiotic and biotic processes, but some may transform into more toxic or persistent compounds; (3) understanding of biocides’ fate under downhole conditions (high pressure, temperature, and salt and organic matter concentrations) is limited; (4) several biocidal alternatives exist, but high cost, high energy demands, and/or formation of disinfection byproducts limits their use. This review may serve as a guide for environmental risk assessment and identification of microbial control strategies to help develop a sustainable path for managing hydraulic fracturing fluids.
Differential impacts of contaminants

- **Man-made chemicals**
  - Impact on water resources
  - Naturally occurring radioactive materials
    - Long-term accumulation of radioactive elements in sediments, soil

- **Halides (chloride, bromide, iodide)**
  - Impact on water resources
  - Contamination of water resources

- **Inorganic contaminants** (ammonium, barium, strontium)
  - Formation of disinfection byproducts
Risks for wastewater management options

Treatment at a brine treatment facility
- Inadequate treatment for halogens;
- Radioactivity in residual solids

Deep well injection
- Induce seismicity

Recycling to hydraulic fracturing
- Limitation by water chemistry (salinity, scaling, radioactivity, boron)
Spreading produced water on roads in NY
Brine disposal sites in Pennsylvania
Electrical conductivity = 106.2 mS
(seawater=35 mS)
Assessment of Effluent Contaminants from Three Facilities Discharging Marcellus Shale Wastewater to Surface Waters in Pennsylvania

Kyle J. Ferral,†‡,* Drew R. Michanowicz,†‡ Charles L. Christen,†§ Ned Mulcahy,† Samantha L. Malone,†‡ and Ravi K. Sharma†⊥‖

Impacts of Shale Gas Wastewater Disposal on Water Quality in Western Pennsylvania

Nathaniel R. Warner,*† Cidney A. Christie, Robert B. Jackson, and Avner Vengosh*


Jessica M. Wilson*† and Jeanne M. Van Briesen‡
Josephine Brine Treatment Facility

Source: Warner et al., 2013, ES&T
A long-term legacy of radioactivity accumulation in river sediments of a disposal site

Radioactivity threshold (requires a licensed radioactive waste disposal facility)

Would spills/leaks/any disposal of hydraulic fracturing fluids induce radioactive legacy?

Iodide, Bromide, and Ammonium in Hydraulic Fracturing and Oil and Gas Wastewaters: Environmental Implications

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Supporting Information

ABSTRACT: The expansion of unconventional shale gas and hydraulic fracturing has increased the volume of the oil and gas wastewater (OGW) generated in the U.S. Here we demonstrate that OGW from Marcellus and Fayetteville hydraulic fracturing flowback fluids and Appalachian conventional produced waters is characterized by high chloride, bromide, iodide (up to 56 mg/L), and ammonium (up to 420 mg/L). Br/Cl ratios were consistent for all Appalachian brines, which reflect an origin from common parent brine, while the I/Cl and NH₄/Cl ratios varied among brines from different geological formations, reflecting geogenic processes. There were no differences in halides and ammonium concentrations between OGW originating from hydraulic fracturing and conventional oil and gas operations. Analysis of discharged effluents from three brine treatment sites in Pennsylvania and a spill site in West Virginia show elevated levels of halides (iodide up to 28 mg/L) and ammonium (12 to 106 mg/L) that mimic the composition of OGW and mix conservatively in downstream surface waters. Bromide, iodide, and ammonium in surface waters can impact stream ecosystems and promote the formation of toxic brominated-, iodinated-, and nitrogen disinfection byproducts during chlorination at downstream drinking water treatment plants. Our findings indicate that discharge and accidental spills of OGW to waterways pose risks to both human health and the environment.
High bromide in flowback and—both unconventional and conventional produced water
High iodide in flowback and—both unconventional and conventional produced water
High ammonium in flowback and—both unconventional and conventional produced water
High radium levels in produced waters from both conventional and unconventional oil and gas wells

Source: Lauer et al., 2015 (in review)
The potential of formation disinfection byproducts in downstream drinking water supplies

Enhanced Formation of Disinfection Byproducts in Shale Gas Wastewater-Impacted Drinking Water Supplies

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Supporting Information

ABSTRACT: The disposal and leaks of hydraulic fracturing wastewater (HFW) to the environment pose human health risks. Since HFW is typically characterized by elevated salinity, concerns have been raised whether the high bromide and iodide in HFW may promote the formation of disinfection byproducts (DBPs) and alter their speciation to more toxic brominated and iodinated analogues. This study evaluated the minimum volume percentage of two Marcellus Shale and one Fayetteville Shale HFWs diluted by fresh water collected from the Ohio and Allegheny Rivers that would generate and/or alter the formation and speciation of DBPs following chlorination, chloramination, and ozonation treatments of the blended solutions. During chlorination, dilutions as low as 0.01% HFW altered the speciation toward formation of brominated and iodinated trihalomethanes (THMs) and brominated haloacetones (HANs), and dilutions as low as 0.03% increased the overall formation of both compound classes. The increase in bromide concentration associated with 0.01–0.03% contribution of Marcellus HFW (a range of 70–200 μg/L for HFW with bromide = 600 mg/L) mimics the increased bromide levels observed in western Pennsylvania surface waters following the Marcellus Shale gas production boom. Chloramination reduced HAN and regulated THM formation; however, iodinated trihalomethane formation was observed at lower pH. For municipal wastewater-impacted river water, the presence of 0.1% HFW increased the formation of N-nitrosodimethylamine (NDMA) during chloramination, particularly for the high iodide (54 ppm) Fayetteville Shale HFW. Finally, ozonation of 0.01–0.03% HFW-impacted river water resulted in significant increases in bromate formation. The results suggest that total elimination of HFW discharge and/or installation of halide-specific removal techniques in centralized brine treatment facilities may be a better strategy to mitigate impacts on downstream drinking water treatment plants than altering disinfection strategies. The potential formation of multiple DBPs in drinking water utilities in areas of shale gas development requires comprehensive monitoring plans beyond the common regulated DBPs.

INTRODUCTION

Hydraulic fracturing and horizontal drilling have significantly expanded the production of natural gas from low permeability fossil fuel reservoirs in the US over the past decade. With production from such unconventional natural gas production facilities anticipated to provide nearly 50% of total US natural gas production over the coming decades, hydraulic fracturing could yield economic benefits, but there are significant concerns regarding the potential adverse impacts on the environment.1 Four categories of concerns have been raised: (1) contamination of overlying drinking water aquifers by leakage of natural gas or saline waters from the production formations through well casings, (2) the quantity of freshwater consumed by hydraulic fracturing operations, (3) long-term contamination of sediments resulting from the binding of radioactive cations in wastewaters to sediments adjacent to wastewater discharge locations, and (4) impacts to downstream drinking water treatment plants resulting from discharges of saline wastewaters to surface waters.2 Wastewaters associated with hydraulic fracturing, including drilling fluids, flowback waters, and produced waters, frequently contain high levels of halides, heavy metals, and radioactivity.3 After Marcellus Shale development began, a fraction of hydraulic fracturing wastewater (HFWs) in Pennsylvania were sent to either public or privately owned treatment works (POTWs) for municipal wastewater treatment or commercial wastewater treatment (CWT) plants for oil and gas wastewaters and subsequently discharged to surface waters.4 Flowback and produced waters typically exhibit elevated chloride and bromide concentrations.5–7 Halides are poorly removed from both POTWs and CWT treatment plants.8 As a result of large volume disposal of HFW from disposal sites in PA (until recently), several studies have reported an increase in

Received: June 9, 2014
Revised: August 30, 2014
Accepted: September 9, 2014
Even a tiny fraction of wastewater in a river could promote the formation of disinfection byproducts.
Spills
Frequency of spills/violations appear to coincide with the intensity of shale gas drilling in PA

Vengosh et al., 2014 (ES&T)
Density of Oil and Gas Wells in North Dakota

Source: Lauer et al., GSA 2015
Density of Brine Spills in North Dakota

Source: Lauer et al., GSA 2015

Brine Spills (2006 - 2014)

- < 100
- 100 - 1,000
- 1,000 - 10,000
- 10,000 - 100,000
- 100,000 - 1,008,000

Prospective Plays

US Shale Plays

Sedimentary Basins

Source: Lauer et al., GSA 2015
Spills in North Dakota
Spills in North Dakota

![Graph showing Spills, Bakken brines, and Ecological threshold]

**Spill contaminants**
- High salts (Cl, Na, Br)
- Ammonium
- Vanadium
- Arsenic
- Boron
- Naturally occurring radioactive elements (\(^{226}\)Ra, \(^{228}\)Ra, \(^{210}\)Pb)

Source: Lauer et al., GSA 2015
Radioactivity legacy in soil

Bear Den Spill, July 2014

100 Bq/kg

Brine location, July 2015

200 Bq/kg
Cases of impact by man-made hydraulic fracturing chemicals

Evaluating a groundwater supply contamination incident attributed to Marcellus Shale gas development

Garth T. Llewellyn\textsuperscript{a,1}, Frank Dorman\textsuperscript{b}, J. L. Westland\textsuperscript{b}, D. Yoxtheimer\textsuperscript{c}, Paul Grieve\textsuperscript{c}, Todd Sowers\textsuperscript{c}, E. Humston-Fulmer\textsuperscript{d}, and Susan L. Brantley\textsuperscript{c,1}

\textsuperscript{a}Appalachia Hydrogeologic and Environmental Consulting, LLC, Bridgewater, NJ 08807; \textsuperscript{b}Department of Biochemistry and \textsuperscript{c}Earth and Environmental Systems Institute and Department of Geosciences, Pennsylvania State University, University Park, PA 16802; and \textsuperscript{d}Leco Corporation, St. Joseph, MI 49085

Edited by Stephen Polasky, University of Minnesota, St. Paul, MN, and approved April 2, 2015 (received for review October 22, 2014)

- Occurrence of a compound identified in flowback, 2-n-Butoxyethanol, was also positively identified in one of the foaming drinking water wells near shale gas wells in Pennsylvania at nanogram-per-liter concentrations (Llewellyn et al., 2014, PNAS);
A study of 64 drinking water wells in PA revealed trace levels of volatile organic compounds, low levels of gasoline range (0–8 ppb) and diesel range organic compounds (DRO; 0–157 ppb). A compound-specific analysis revealed the presence of bis(2-ethylhexyl) phthalate, which is a disclosed hydraulic fracturing additive. Integration of water geochemistry and noble gas data suggest DRO transport to groundwater via accidental release of fracturing fluid chemicals derived from the surface rather than subsurface flow of these fluids from the underlying shale formation (Drolette et al., 2015, PNAS).
Part Four: Identification of hydraulic fracturing fluids in the environment

• Identification of hydraulic fracturing fluids in the environment is critical for environmental management, regulations, and remediation plans.
• Man-made chemicals added to hydraulic fracturing fluids are not always stable and their occurrence and distribution is typically unknown.
• Isotopic tracers of the inorganic constituents associated with formation waters is a promising tool.
Tracing hydraulic fracturing fluids in the environment

Warner et al. (2014)
Radium isotopes as a tracer to identify source of contaminated water and to distinguish conventional from unconventional wastewater source

Source: Lauer et al., Duke University
Water contamination

Implications for the UK:

• Monitoring and baseline studies must include integrated and comprehensive dataset, including inorganic and trace elements, stable, ($\delta^{18}$O, $\delta^2$H, $\delta^{13}$C, dissolved ions isotopes ($^{87}$Sr/$^{86}$Sr, $\delta^{11}$B), and radionuclides ($^{226}$Ra, $^{228}$Ra).

• Research focus on elucidating the occurrence of naturally occurring contaminants in hydraulic fracturing fluids.
Conclusions

- Much attention has been given to man-made chemicals in hydraulic fracturing and their risks to human health and the environment. Yet inorganic chemicals, including halides, ammonium, trace elements, and NORMs pose as much, if not more, risk.

- Stray gas contamination is real with independent geochemical evidence for shale gas leaking and contamination of a subset of wells near shale gas exploration (PA, TX).

- Wastewater is one of the major challenges associated with the rising of unconventional oil and gas if it cannot be disposed through deep-well injection.
Acknowledgements

• Nicholas School of Environment, Duke University;

• National Science Foundation, Geobiology & Low-Temperature Geochemistry Program;

• Park Foundation;

For more information and publications:

http://sites.nicholas.duke.edu/avnervengosh/
UK Perspectives on Water Quality and Availability

Rob Ward

Director of Groundwater Science
British Geological Survey
Outline

- Groundwater regulation, management and protection in the UK
- Water requirements and availability
- Pollution risk assessment/management and monitoring
Groundwater protection

- Groundwater protection/management strategies in the UK delivered by environment agencies:
  - Ensures consistent application of EU Directives and UK regulations
  - Protects groundwater as a resource and its environmental function (now and in future)

- Protection Policy and Position Statements supported by management tools, including:
  - Groundwater vulnerability maps
  - Source Protection Zones/Safeguard Zones
  - Risk assessment models
  - Abstraction licencing (CAMS)
Changing legislation landscape

- **Infrastructure Act 2015** – Onshore hydraulic fracturing: safeguards (*selected*):
  - No hydraulic fracturing at depths <1000m
  - Independent inspection on well integrity
  - Baseline monitoring for CH$_4$: in the 12 months before
  - No hydraulic fracturing on GW protection zones* or other protected areas
  - Cumulative effects to be considered
  - Fracking chemicals must be approved
  - Water companies to be statutory consultees

* Draft Regs to elaborate - propose SPZ1 and <1200 m depth. Also consultation launched on protected areas (4 Nov 2015)
Water resource demand and impact

- Water demand for 100 individual wells per year drilled/stimulated: 1.5 – 2.4 million cubic metres/year
- Total annual licensed non-tidal abstraction for England and Wales: 14,120 million cubic metres

Resource availability - percentage of time available

All freshwater abstraction (2013 data) - Percentages

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2015, England and Wales
Source: www.gov.uk/government/statistical-data-sets
Shale and aquifer mapping

GB3D BGS National Geological Model

Shaded area prospective for shale oil
Baseline monitoring objectives

• Respond to public concerns and need for good practice
• Establish independent science-based monitoring programme
• Provide high resolution data, knowledge and scientific results to:
  - Inform public, industry, regulators of environmental baselines and their variability
  - Assist in shaping regulatory monitoring and good practice
  - Improve understanding to avoid issues encountered in North America
  - Enable new monitoring technology
  - Deliver an effective partnership to build UK capability
1. Measurements:
- Dissolved concentrations of CH₄ and CO₂ plus general water chemistry
- Stable isotopes of CH₄ and CO₂
- Trace organics
- Groundwater residence time indicators
- Other baseline data (EA, BGS etc)
- Temporal variation (12 mths)

3. Publication:
- Data summaries/statistics/interpretation on BGS website
Lancs/Yorks water quality monitoring

- **Existing boreholes**
  - Public/private water supply boreholes, EA boreholes

- **New boreholes**
  - 6 x pairs shallow (<40m) and 2 x deep (c 250 m)
  - Third Energy monitoring boreholes?

- **Sampling/analysis for**
  - Inorganic and organic chemistry,
  - Dissolved gases (incl. CH₄, noble gases)
  - Stable isotopes and residence time indicators tracers
  - NORM
Groundwater baseline (Lancs)
Well integrity: aquifers and wells

- 2152 hydrocarbon wells drilled onshore since 1900
- Only two well integrity issues reported
- No evidence of wide-scale impacts on groundwater

However......

- No systematic monitoring
- 45% drilled through drinking water aquifers:
  - 20% Principal aquifer
  - 25% Secondary aquifer
- Project to investigate evidence of impact

Aquifer Classification
- Intergranular flow aquifers
  - Highly productive aquifer
  - Moderately productive aquifer
  - Low productivity aquifer
  - Fracture flow aquifers
- Highly productive aquifer
- Moderately productive aquifer
- Low productivity aquifer
- Rocks with essentially no groundwater

from Davies et al, 2014
Key research questions

- Characterisation of the deep sub-surface (>400 m) to understand:
  - Pathway characteristics - hydrogeological properties
  - System response to anthropogenic influences
  - Behaviour and interactions of fluids (physical, chemical, biological)
- Risk evaluation – natural and anthropogenic exposure pathways, long term behaviour
- Detailed characterisation of baseline – spatial/temporal variation
Thank you

www.bgs.ac.uk/research/groundwater
US Experience on Wastewater Treatment, Disposal and Reuse

Radisav D. Vidic

Department of Civil and Environmental Engineering
University of Pittsburgh, Pittsburgh, PA 15261

Joint US-UK Workshop on Improving Understanding of Potential Environmental Impacts Associated with Unconventional Hydrocarbons

November 5-6, 2015
Unconventional Gas Production in Pennsylvania

![Graph showing the increase in TCF from 2010 to 2014.](chart.png)
Wastewater Generated by Unconventional Gas Production in Pennsylvania
Conventional Water Management Flow Scheme 1

- ~30,000 Class II disposal wells in the US
- Dominant approach in most shale plays
- Represents Maximum Water Demand
- Difficult in Marcellus (only 7 Class II wells)
Class II Disposal Wells in PA, OH, WV
On-Site Primary Treatment for Reuse Flow Scheme 2

- Well 1
- On-Site SS Removal
- Well 2
- Blend
- High TDS Reuse Water
- Makeup Water (Fresh Water)
Off-Site Primary Treatment for Reuse
Flow Scheme 3

Well 1

On-Site SS Removal

Rapid Mix w/ chemicals

Sedimentation & Hardness Rem

Rapid Sand Filter

Belt Press

Solids to Landfill

Disinfect

Near-Field Primary Treatment

High TDS Water For Reuse

Blend

Makeup Water (Fresh Water)

Well 2

Well 2
Off-Site Primary Treatment and Demineralization Flow Scheme 4

1. On-Site SS Removal
2. Near Field Primary Treatment
3. Demineralization (e.g., MVR)
4. Distilled Water For Reuse
5. Makeup Water (Fresh Water)
6. Blend
7. Concentrated Brine
8. Disposal (Class II Well) Or By-Product Recovery (Crystallizer)
# Economic Comparison of Flow Schemes

*Basis: 1 million gallons of flowback (23,800 barrels)*

<table>
<thead>
<tr>
<th>Flow Scheme</th>
<th>FS 1</th>
<th>FS 2</th>
<th>FS 3</th>
<th>FS 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Method</strong></td>
<td>Transport to Class II Well for Disposal</td>
<td>“In Field” Primary Treatment for Reuse</td>
<td>“Near Field” Precipitation for Reuse</td>
<td>“Near Field” Evaporation for Reuse</td>
</tr>
<tr>
<td>Treatment $</td>
<td>-</td>
<td>71</td>
<td>83</td>
<td>119</td>
</tr>
<tr>
<td>Transport $</td>
<td>75</td>
<td>1</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Brine Disposal $</td>
<td>60</td>
<td>-</td>
<td>-</td>
<td>19</td>
</tr>
<tr>
<td>Sludge Disposal $</td>
<td>-</td>
<td>2</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Total Cost ($x1000)</td>
<td>135</td>
<td>74</td>
<td>113</td>
<td>168</td>
</tr>
<tr>
<td>Cost per barrel</td>
<td>5.67</td>
<td>3.10</td>
<td>4.75</td>
<td>7.05</td>
</tr>
<tr>
<td>Hardness Removal</td>
<td>100%</td>
<td>0%</td>
<td>97%</td>
<td>100%</td>
</tr>
<tr>
<td>Ba removal</td>
<td>100%</td>
<td>0%</td>
<td>99%</td>
<td>100%</td>
</tr>
<tr>
<td>Salt Removal</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
<td>100%</td>
</tr>
<tr>
<td>Water reused</td>
<td>0</td>
<td>99%</td>
<td>97%</td>
<td>90%</td>
</tr>
</tbody>
</table>
Complete Treatment Process

WATER SOURCE → FRAC OPERATIONS → WASTE BRINE STORAGE

FLOWBACK

PRODUCED WATER

WASTE BRINE STORAGE

Pretreatment

RECOVERED WATER

SALT → BRINE CRYSSTALLIZER

Volume Reduction Based on TDS

95% Volume Reduction

PURGE TO DISPOSAL

BRINE CONCENTRATOR

Civil and Environmental Engineering
### How to Satisfy All Criteria?

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Limit</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Fe &gt;25 ppm</td>
<td></td>
<td>Impacts hydration and thermal stability of polymer and/or crosslinker.</td>
</tr>
<tr>
<td>Cl⁻ &gt;200 ppm</td>
<td></td>
<td>Interference with buffers in crosslink systems. Some friction reducers are prone to precipitation.</td>
</tr>
<tr>
<td>SO₄²⁻ &gt;200 ppm</td>
<td></td>
<td>Interferes with delayed metallic crosslinkers. High temperature thermal stability also impacted.</td>
</tr>
<tr>
<td>HCO₃⁻ &gt;600 ppm</td>
<td></td>
<td>Requires pH adjustment for polymer hydration. Zr crosslinkers (delay and/or stability)</td>
</tr>
<tr>
<td>PO₄³⁻ &gt;600 ppm</td>
<td></td>
<td>Interferes with metallic crosslinkers. Reduces fluid performance.</td>
</tr>
<tr>
<td>B &gt;4 ppm</td>
<td></td>
<td>Can cause crosslinking in guar gelling</td>
</tr>
</tbody>
</table>

- **pH**
- **Ferric iron (Fe³⁺)**
- **Ferrous iron (Fe²⁺)**
- **Total hardness**
- **Magnesium (Mg²⁺)**
- **Bicarbonate (HCO⁻³)**
- **Sulfate (SO₄⁻²)**
- **Phosphate (PO₄⁻³)**
- **Silica (Si⁴⁺)**
- **Boron (B⁺³)**
- **Total dissolved solids (TDS)**
- **Total suspended solids (TSS)**
- **Bacteria**

**Nearly every produced water will push these limits**

**Too High > 9.0**: Poor hydration.

**Too Low < 6.0**: Poor dispersion.
## Frac Fluid Design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Limit</th>
<th>Consideration</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>6.0 – 8.0</td>
<td>Fluid stability, Scaling</td>
</tr>
<tr>
<td>Chlorides</td>
<td>&lt; 20,000 mg/L</td>
<td>Fluid stability</td>
</tr>
<tr>
<td>Iron</td>
<td>&lt; 20 mg/L</td>
<td>Fluid stability</td>
</tr>
<tr>
<td>Ca, Mg, Ba, SO\textsubscript{4}, CO\textsubscript{3}</td>
<td>f(P, T, pH) (~350 mg/L)</td>
<td>Scaling</td>
</tr>
<tr>
<td>Bacteria Count</td>
<td>&lt; 100/100 mL</td>
<td>Bacterial growth</td>
</tr>
<tr>
<td>Suspended Solids</td>
<td>&lt; 50 mg/L</td>
<td>Well plugging</td>
</tr>
<tr>
<td>Oil and Soluble Organics</td>
<td>&lt; 25 mg/L</td>
<td>Fluid stability</td>
</tr>
</tbody>
</table>

Hydraulic Fracturing Expert Panel, 9/26/07
Water Quality Considerations

• Who makes the decision?
  - In-house engineer, completions engineer, sales engineer

• Water quality requirements should be developed based on actual water chemistry

• Economics drives the choices
  - Focus on minimal water treatment to promote reuse

• Key driver for water quality requirements is the frac fluid performance
Hydraulic Fracturing Systems

- Slickwater
- Linear Gel
- Cross-linked Gel
Friction reduction is the key issue with pure slickwater fracturing.
Friction Reduction Testing (FR Loop)

\[
\%\text{DR} = \frac{\Delta P_{\text{water}} - \Delta P_{\text{frac fluid}}}{\Delta P_{\text{water}}} \cdot 100
\]

- Decrease due to shear degradation in the pump
- Delay due to FR hydration
### Friction Reducer Performance Criteria based on Friction Loop Performance

<table>
<thead>
<tr>
<th>Sustained %DR for 3 min</th>
<th>&lt;30</th>
<th>&lt;45</th>
<th>&lt;60</th>
<th>&lt;90</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 70</td>
<td>Best</td>
<td>Good</td>
<td>Maybe</td>
<td>Poor</td>
</tr>
<tr>
<td>&gt; 60</td>
<td>Good</td>
<td>Maybe</td>
<td>Poor</td>
<td>Not Acceptable</td>
</tr>
<tr>
<td>&gt; 50</td>
<td>Maybe</td>
<td>Poor</td>
<td>Not Acceptable</td>
<td>Not Acceptable</td>
</tr>
<tr>
<td>&gt; 40</td>
<td>Poor</td>
<td>Not Acceptable</td>
<td>Not Acceptable</td>
<td>Not Acceptable</td>
</tr>
<tr>
<td>&gt; 30</td>
<td>Not Acceptable</td>
<td>Not Acceptable</td>
<td>Not Acceptable</td>
<td>Not Acceptable</td>
</tr>
</tbody>
</table>

Kidder, M. SPE Workshop, Ft. Worth, TX, March 2013.
## Friction Reducer Compatibility Criteria

<table>
<thead>
<tr>
<th>FR at 0.5 gal/1,000 gal</th>
<th>Fresh Water System</th>
<th>Moderate Brine System</th>
<th>Heavy Brine System</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDS (mg/L)</td>
<td>&lt; 10,000</td>
<td>&lt; 20,000</td>
<td>~ 100,000 (limit not yet defined)</td>
</tr>
<tr>
<td>Total Multivalent Cations (mg/L)</td>
<td>&lt; 1,000</td>
<td>&lt; 5,000</td>
<td>~ 15,000 (limit not yet defined)</td>
</tr>
<tr>
<td>pH</td>
<td>&gt; 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>1-2 min to hydrate when T &lt; 50F</td>
<td>30-45 s when T &lt; 50F</td>
<td>(increase FR conc. to improve hydration time)</td>
</tr>
</tbody>
</table>

Kidder, M. SPE Workshop, Ft. Worth, TX, March 2013.
Linear Gel System

- Guar gum or its derivatives
  - Hydroxy-propyl-guar (HPG)
  - Carboxy-methyl-hydroxy-propyl-guar (CMHPG)
- Cellulose derivatives
  - Hydroxy-ethyl-cellulose (HEC)
- Require moderate pH (6-8) to ensure proper hydration
- Guar is insensitive to:
  - High TDS
  - Multivalent (hardness) ions
- Crosslinkers (aluminum, boron, titanium, zirconium) should be minimized to reduce the risk of accidental cross-linking in the event of unexpected pH increase
Guar – Borate System

• Generally adaptable to a variety of water conditions
• Desirable characteristics for proppant placement (early viscosity, shear recovery)
• Requires high pH (8.5 to >12)
  - Low temperature (8.5 to 10.0)
  - High temperatures require higher pH (10.0 to >12)
• Limited performance above 300°F
High Alkalinity Water Challenging for Guar-Borate

High pH is necessary for borates to crosslink guar gel

High pH accelerates scaling
Metallic crosslink system

- More potential issues with challenging waters
- Flexible pH (4 to 11)
- Must be properly delayed (shear degrading)
- Balancing delay and early crosslinking/viscosity is difficult
- Existing crosslinked packages developed for fresh water
- Adapting fluids to more challenging conditions
Performance Testing

Bjornen, K. et al. SPE Workshop, Ft. Worth, TX, March 2013.
- Lead off with a simple slickwater fluid with 100 mesh proppant
- Switch to a linear guar gel and larger proppant
- Finish with a higher proppant loading and X-linked gel

Need to satisfy ALL water quality criteria
## Water Quality Requirements

<table>
<thead>
<tr>
<th>Property</th>
<th>Acceptable Range</th>
<th>Affected</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDS</td>
<td>&lt; 30,000 mg/L</td>
<td>FR / Hydration</td>
</tr>
<tr>
<td>Total Hardness</td>
<td>&lt; 10,000 mg/L</td>
<td>FR / Hydration</td>
</tr>
<tr>
<td>(Ca + Mg + Ba + Sr)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfates</td>
<td>&lt; 200 mg/L</td>
<td>Scaling tendency</td>
</tr>
<tr>
<td>pH</td>
<td>6-8</td>
<td>Hydration</td>
</tr>
<tr>
<td>Carbonates</td>
<td>&lt; 200 mg/L</td>
<td>Scaling tendency</td>
</tr>
<tr>
<td>Bicarbonate</td>
<td>&lt; 400 mg/L</td>
<td>Scaling tendency</td>
</tr>
<tr>
<td>Reducing agents</td>
<td>0 ppm</td>
<td>Hydration / Breaker</td>
</tr>
<tr>
<td>Silica</td>
<td>&lt; 1 mg/L</td>
<td>Crosslinking</td>
</tr>
<tr>
<td>Iron</td>
<td>&lt; 10 mg/L</td>
<td>Crosslinking / Hydration</td>
</tr>
<tr>
<td>Phosphates</td>
<td>&lt; 5 mg/L</td>
<td>Crosslinking</td>
</tr>
<tr>
<td>Bacteria</td>
<td>&lt; $10^5$/mL</td>
<td>Gel / Crosslinking</td>
</tr>
</tbody>
</table>
Dissolved ions (chlorides and TDS)
- Generally not looking to remove; blending with fresh water is the control strategy

Other dissolved constituents

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Above Ground</th>
<th>In-well</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness</td>
<td>Softening</td>
<td>Complexation</td>
</tr>
<tr>
<td>Barium</td>
<td>Sulfate precipitation</td>
<td>Complexation</td>
</tr>
<tr>
<td>Iron</td>
<td>Aeration</td>
<td>Complexation</td>
</tr>
</tbody>
</table>

Suspended solids (turbidity and TSS)
- Can decrease biocide effectiveness
- Remove by filtration
Summary

- Produced water reuse depends on both quantity and quality
- Water reuse can be more cost effective than disposal
- Water compatibility with frac fluid design governs treatment requirements
  - Slickwater: easy to reuse water by choosing the right friction reducer
  - Linear Gels: as long as pH does not increase above 8, similar criteria as for slickwater
  - Cross-linked Gels: Multivalent cations and crosslinker concentration in the produced water are important criteria; residual gel may be a concern
Research Needs

Water reuse

- Revise old water quality criteria for reuse based on specific applications and compatibility tests
- Develop new additives to extend water reuse
- Determine optimal chemical composition of frac fluid to ensure an effective frac without excessive treatment
- Identify maximum TDS, bacteria, barium, chloride and pH levels that can be present without causing scaling, corrosion or friction
- Evaluate optimal water chemistry for gel fracs to carry optimal volumes of proppant while still being cost effective

Water treatment

- Develop new cost-effective technologies for produced water treatment once the reuse is no longer feasible

\[ \sigma_{hmin} = 5324 \text{ psi} \]
\[ \sigma_{Hmax} = 5524 \text{ psi} \]
The UK perspective on Wastewater Treatment, Disposal and Reuse

Joint US-UK workshop on Improving Understanding of Potential Environmental Impacts Associated with Unconventional Hydrocarbons

Dr Frederic Coulon

05/11/2015

www.cranfield.ac.uk
Overview of the water cycle and shale gas waste streams

1. **Produced water**: naturally occurring water found in shale formations that flows to the surface throughout the entire lifespan of the gas well.
2. **Flowback water**: Fracturing fluids returning to the surface, also called returned water.
3. **Drilling mud/fluid**: A mixture of liquids and gaseous fluids and mixtures of fluids and solids used to drill into the earth.

Note: All three also likely to include fracking chemicals, heavy metals & radiological materials.

1. **Brine**: Salt water also called formation water.
2. **Flowback fluid**: Recovered fracturing fluids, also called produced water.
3. **Drilling mud/fluid**: A mixture of liquids and gaseous fluids and mixtures of fluids and solids used to drill into the earth.

Note: 20% to 40% of injected water recovered.
### Water management: challenges to overcome and options

<table>
<thead>
<tr>
<th>Securing raw water</th>
<th>Avoid/reduce water production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hauling to sewage plants (hydrocarbon and chloride issues)</td>
<td>Polymer gels</td>
</tr>
<tr>
<td>Hauling and dumping cost are expensive and will continue to rise</td>
<td>Downhole separators</td>
</tr>
<tr>
<td>Treated water often not returned to source</td>
<td>Reduce volume at surface</td>
</tr>
<tr>
<td>Overcoming environmental concerns</td>
<td>Surface impoundment for evaporation</td>
</tr>
<tr>
<td></td>
<td>Solid settlement</td>
</tr>
<tr>
<td></td>
<td>Direct reuse</td>
</tr>
<tr>
<td></td>
<td>Blending with freshwater without treatment</td>
</tr>
<tr>
<td></td>
<td>Low costs but potential for well plugging</td>
</tr>
<tr>
<td></td>
<td>Convert salt to road deicer</td>
</tr>
<tr>
<td></td>
<td>Discharge into the environment</td>
</tr>
<tr>
<td></td>
<td>Direct discharge if meets standard</td>
</tr>
<tr>
<td></td>
<td>Pre-treatment before discharge to treatment works</td>
</tr>
</tbody>
</table>
Flow back and water treatment: the water loop – Treat and Reuse

Water supply source options
1. Municipal supply vs self supply
   - Dependent on location, availability, timing
   - Municipal supply access generally quicker but much costlier
2. Surface waters vs groundwater
   - GW primary source
   - GW wells may work well economically and logistically where sufficient yields can be obtained
3. Alternative water sources
   - Abandoned mine drainage
   - Wastewater
   - Cooling water
   - others
Other example of closing the loop: treat and reuse

Water storage options
- Centralised impoundment
- Single pad-dedicated impoundment
- Frac tanks
- Storage based on ultimate scale of operations (short vs long-term)

Figure 2: ENVIRON's Zero Water Discharge process.
Some chemicals used in "Fracking"

<table>
<thead>
<tr>
<th>Compound</th>
<th>Purpose</th>
<th>Common application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acids</td>
<td>Helps dissolve minerals and initiate fissure in</td>
<td>Swimming pool cleaner</td>
</tr>
<tr>
<td></td>
<td>rock (pre-fracture)</td>
<td></td>
</tr>
<tr>
<td>Sodium Chloride</td>
<td>Allows a delayed breakdown of the gel polymer</td>
<td>Table salt</td>
</tr>
<tr>
<td></td>
<td>chains</td>
<td></td>
</tr>
<tr>
<td>Polyacrylamide</td>
<td>Minimizes the friction between fluid and pipe</td>
<td>Water treatment, soil conditioner</td>
</tr>
<tr>
<td>Ethylene Glycol</td>
<td>Prevents scale deposits in the pipe</td>
<td>Automotive anti-freeze, deicing agent,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>household cleaners</td>
</tr>
<tr>
<td>Borate Salts</td>
<td>Maintains fluid viscosity as temperature</td>
<td>Laundry detergent, hand soap, cosmetics</td>
</tr>
<tr>
<td></td>
<td>increases</td>
<td></td>
</tr>
<tr>
<td>Sodium/Potassium</td>
<td>Maintains effectiveness of other components,</td>
<td>Washing soda, detergent, soap, water</td>
</tr>
<tr>
<td>Carbonate</td>
<td>such as crosslinkers</td>
<td>softener, glass, ceramics</td>
</tr>
<tr>
<td>Glutaraldehyde</td>
<td>Eliminates bacteria in the water</td>
<td>Disinfectant, sterilization of medical and</td>
</tr>
<tr>
<td></td>
<td></td>
<td>dental equipment</td>
</tr>
<tr>
<td>Guar Gum</td>
<td>thickens the water to suspend the sand</td>
<td>Thickener in cosmetics, baked goods, ice</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cream, toothpaste, sauces</td>
</tr>
<tr>
<td>Citric Acid</td>
<td>Prevents precipitation of metal oxides</td>
<td>Food additive; food and beverages; lemon</td>
</tr>
<tr>
<td></td>
<td></td>
<td>juice</td>
</tr>
<tr>
<td>Isopropanol</td>
<td>Used to increase the viscosity of the fracture</td>
<td>Glass cleaner, antiperspirant, hair</td>
</tr>
<tr>
<td></td>
<td>fluid</td>
<td>coloring</td>
</tr>
</tbody>
</table>
Many Operators Now Treating and Reusing Frack Water Flow Back

Summary of Management Options for Shale Gas Wastewater

On-Site Management

- Flowback or Produced Water
- Direct reuse within flowback (typically with dilution)
- Minimization of produced water

Off-Site Management

- Holding Ponds or Tanks and On-site Treatment
- Transport
- Off-site Treatment
- Disposal
- Beneficial reuse

- Reuse of treated wastewater
- Disposal into underground injection wells
- Surface discharge

Natural Resources Defense Council report (2012)

http://www.environmentalleader.com/2012/05/14/stricter-regulatory-standards-end-of-legal-loopholes-needed-for-fracking-safety-nrdc-says/
## Treatment technologies and costs

<table>
<thead>
<tr>
<th>Technology</th>
<th>Actions</th>
<th>Cost per barrel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filtration and disinfection</td>
<td>TSS removal and biocide</td>
<td>$0.50-1</td>
</tr>
<tr>
<td>Membrane technologies</td>
<td>TDS removal including minerals</td>
<td>High capital and operating costs: $3-10</td>
</tr>
<tr>
<td>Thermal distillation</td>
<td>Production of high (distilled water)</td>
<td>Energy intensive and higher costs than alternatives</td>
</tr>
<tr>
<td>Ion Exchange</td>
<td>Target specific pollutants</td>
<td>$2-8</td>
</tr>
<tr>
<td>Electrocoagulation</td>
<td>Removed charged particles attached to metals - Issues with metal corrosion and durability</td>
<td>$2-5</td>
</tr>
<tr>
<td>Chemical precipitation</td>
<td>Metal precipitation - Robust technology and can be combined with various treatment</td>
<td>$1-5</td>
</tr>
<tr>
<td>Precipitative Softening</td>
<td>pH adjustment, precipitation H.M., removal phosphates, sulfates and fluorides</td>
<td>$2-4</td>
</tr>
</tbody>
</table>

Schantz and Kramadhati, 2014, Lhoist North America
Parameters of concern for reuse of flowback water

- Total dissolved solids (chloride) – interference with friction reducers
- Total suspended solids – down hole plugging
- Heavy metals (barium and strontium) – may form precipitates
- Naturally-occurring radioactive materials (NORMs) - Ra is chemically similar to Ca; Ra co-precipitates with Ba; Ra will deposit on surfaces
- Sulfates and carbonates – may form precipitates
- Bacteria – down hole plugging

Many municipal wastewater treatment plants have been designated for disposing of flowback, but are not equipped or designed to handle these fluids, particularly because of high Total Dissolved Solids (from brine), NORMs, & other chemicals
Potential problems from recycling

- Recycled fracking fluids need to be filtered
  - to remove sand, rock cuttings, etc. before being reused
- Filtered materials go to landfills
- Reusing the fluid increases the levels of Radium each time through, not removed
- Eventually TDS etc. so high that fluid must be disposed of in Class II wells\(^1\) anyway in US

\(^1\) [http://water.epa.gov/type/groundwater/uic/class2/]
UK concerns, challenges and perspectives

1. Recovery and storage of flow-back water
   - must be captured at the surface and stored on-site until hauling for treatment
   - Accidents during the handling and transfer of fluids can affect local environment and human health
   - Little evidence is available to describe the fate and transport of the hydraulic fracturing fluids that remain in the shale.

2. Treatment of flowback water
   - Unable to re-inject flow-back fluids into shale wells for disposal - operators must seek treatment options.
   - Municipal wastewater treatment facilities are not fit for purpose - treating large volumes of flow-back fluids
   - Logistics and capacity of industrial water treatment facilities uncertain.
   - Treatment of flow-back fluids has been shown to pose a risk to downstream water quality (i.e. high dissolved solid loading) thus necessitating development of a water treatment strategy.
3. Recycling flow-back water:
   • UK regulations do not permit the re-injection of flow-back fluids into shale gas wells for the purpose of disposal.
   • This practice differs from the US where reinjection of flow-back fluids, or brine water, is common practice.
   • Rules about the re-use of flow-back fluids for subsequent fractures is still under discussion.
   • If flow-back fluids are to be used for subsequent hydraulic fractures they will require treatment.
   • Water treatment is costly (e.g. transport, treatment, disposal), however, solutions that provide on-site treatment, in compliance with local regulation, might provide a cost-effective solution.

4. Water use (scale-up)
   • Demand for water for hydraulic fracturing will place increased stress on water usage.
   • In the US, some states have sought to ban hydraulic fracturing with water altogether (e.g. New York).
   • Technologies that reduce or eliminate water use are needed.
UK context: management of flowback and produced water

- Flowback and produced water: expected to range between 1,000 to 10,000 m$^3$ per well based on anecdotal evidence from the US and subject to the geological conditions encountered.

- Within Europe, flowback and produced water is classified as mining (or ‘extractive’) waste under the EU Mining Waste Directive.

- Operator is required to obtain an environmental permit from the EA (NRW, NIEA or SEPA) to send the water to a wastewater treatment works, or to safely dispose of the returned water.
UK context: Water treatment and reuse

Overall financial cost of compliance with the UK and EU’s robust water regulation regime.

Radioactive Substances Regulation limits the waste may need to be transported further for treatment which would increase costs in addition to the further cost to treat waste to a higher standard.

Very little disposal capacity at present for non-nuclear radioactive waste, which is normally considered to be Very Low or Low Level Radioactive Waste. This might elevate risk considerations where additional storage and transport are required.

Technological advances in terms of fracturing processes which require less water, thus producing less flowback and produced water for subsequent treatment.
Need for integrated water solutions

Hydraulic

Suspended Solids

Ionic Load

Organic Load
A multidisciplinary approach guided by a life cycle systems perspective

Research and technology innovations needs in:
- nanotechnology
- biotechnology
- Water chemistry
- Water reuse and discharge
- Urban water management
- Low energy treatment capability and efficiency

Collaboration with policy experts to find transformative practical solutions and enable Integrated Water Management to achieve sustainable water management and address challenges of the energy-water nexus
Need for transforming water treatment to reduce carbon emission

Potential responses available to the water industry:

1. Source control
2. Least-carbon end-of-pipe/process addition
3. Greater operational efficiencies
4. Redeveloping existing treatment processes
5. Energy generation
An opportunity? using captured CO$_2$ for shale gas production

The cost of CCS is a major barrier to its deployment. However, there are circumstances where disposition of the captured CO$_2$ can generate revenue which offsets the cost, such as the case of enhanced oil recovery by injection of CO$_2$. We have been exploring another possibility: using captured CO$_2$ for shale gas production. This application may not only generate revenue, but also address pressing environmental issues.
Using captured CO$_2$ for shale gas production

Using CO$_2$ would save large quantities of water, which has limited supply in many parts of the world. Besides, it would eliminate the costs of treatment/disposal of waste water.

Injection of CO$_2$ would enhance shale gas recovery.

CO$_2$ could displace methane from shale.

Experimental results suggest that five moles of CO$_2$ can be adsorbed in shale for one mole of CH$_4$ desorbed.
Wrap up on the concerns about water

- **Quantity**
  - 1-2 million gallons/drill (8400 m\(^3\) @ Preese Hall fracs)
  - 2-5 million gallons/hydraulic fracture (9000 – 22730 m\(^3\))
  - After the frac water is injected into the well, some returns immediately to surface, usually around 20% to 40%

- **Quality**
  - Chemicals, mixture
  - Hydraulic fracturing, drilling muds and additives, naturally occurring radioactive materials (NORM), salinity (Marcellus brine – 250,000 mg/L ; 10 fold seawater);
  - High bromide, bromide presence in water enhances the formation of carcinogenic disinfection by-products (e.g., bromodichloromethane) upon chlorination of downstream potable water;

- **Disposal**
  Salts, metals (barium, arsenic, selenium, lead); hydrocarbons, NORM (5000 pCi/L, drinking water standard=5 pCi/L)

- **Wastewater volume, treatment and reuse and energy requirement**
Can we develop sustainable and technical sound solutions?

- Based on the concept of sustainability, can we develop technical solutions to minimize water use, maximize water recovery and reuse and/or use alternative fluids?

**Key research areas:**

- On-site integrated shale gas waste water treatment
- Water use reduction – enhanced chemistry and water technology
- Use of alternative extraction fluids to reduce water footprint
- Development of a zero liquid discharge
- Management of subsurface effects
APPENDIX C: TOP NEAR-TERM AND LONGER-TERM RESEARCH PRIORITIES IDENTIFIED BY PARTICIPANTS

At the end of each of the two days the participants were asked to write down a short and long term research gap or question on a post-it note. These notes were then collated into groups by the conveners, Danny Reible and Richard Davies.

C.1 Research priorities reported for Day 1 themes: Whole-system approaches, seismicity, and air quality

C.1.1 Near term *(during the coming year)*

1. **Socioeconomic/community** (12)
   a. What are the key points of intersection between energy and environmental (land use, water quality, etc.) systems; this will help identify priority economic impacts for research
   b. Energy – the “haves” (U.S.) and the “have nots” (EU) will have to resolve “marketplace” exports and imports worldwide, i.e., a free market supply and demand
   c. How transferable is U.S. knowledge on environmental impacts to UK scenario?
   d. In the UK do we have an industry (potential), e.g., understanding the geology – will inform potential products and hence impacts
   e. More research on the “bust” phase on local communities; what’s next
   f. What are the community and resident impacts of “the bust”? (now is the time to research it)
   g. To what extent does the geographic scale of hydraulic fracturing in the U.S. distinguish it from other activities that create environmental risks
   h. Collect empirical information on the nature of government-industry-public interactions regarding shale gas development permitting and regulation
   i. Has a transparent, open, participatory process for shale gas siting, operations, monitoring and benefits-sharing reduced conflict, or can it?
   j. Data science (for making sense of disparate multi-modal data) to make regulatory decisions and compare practices more data driven / efficient
   k. Understanding the (net positive + negative) socioeconomic impacts of shale gas development at the local scale over the short/medium term
   l. What are the longitudinal changes in public attitudes to hydraulic fracturing?
   m. Research in evaluating the most effective approach(es) for better engaging community and changing public opinion/trust related to hydraulic fracturing
   n. Environmental, economic, social tradeoffs associated with alternative wastewater management and disposal practices; examples: (1) environmental impacts of limiting use of disposal wells due to potential seismicity, (2) comparing trucks vs. pipelines for management, environmental impact, social, cost

2. **Emissions/air quality** (7+3)

   **Super-emitters** (3)
   a. Locate super-emitters of CH4 and have industry eliminate them
   b. Identifying indicators of super-emitting sources for predicting/early detection
   c. What is the cheapest and most effective technique for isolating methane super-emitters?
Additional (7)

a. The comparative emissions from the range of energy options available to the UK at present
b. Baseline data on CH4 emission? What is it going to tell us? go/no go for shale?
c. Developing tools to link air quality parameters to human health (tracers, bioindicators)
d. Health effects and air quality impacts associated with sand proppant or synthetic proppants including related issues with naturally occurring radioactive material (NORM) and solids management
e. Flaring reduction technologies
f. How do we create a nested/affordable/trustworthy monitoring infrastructure to let us discriminate sources and pathways and context of emissions for all media
g. Establish baseline values in terms of groundwater audits, air quality, public health, etc.

3. Seismicity, geomechanics (10)

a. Monitor/measure growth of fracks/fracture networks
b. Investigate hydrogeological controls and responses to seismicity initiated by HF; measurement data and modeling
c. Data from injection reservoirs to predict seismic activity; pressure data
d. Geochemical response to induced seismicity and its effects on flow
e. Understanding seismic signatures of injection wells, “earthquake precursors”
f. Considering the fact that locating the faults is not completely possible, and also we have seen that induced seismicity is happening, how can we make sure that developing hydraulic fracturing will not cause big fatal earthquakes?
g. What baseline monitoring is required now to monitor/understand how deformation and fluids lead to seismicity and leakage?
h. In the short run, I think we should do more research on the impacts of hydraulic fracturing and wastewater injection on seismicity – predicting the pressure distribution below the injection line
i. Ways to reuse water or keep it downhole (don’t produce it); reduces surface activity, minimize injection and seismicity
j. Drill to get data

4. Frameworks, models, methods (4)

a. Technological/management methods to reduce the potential risk factors (wastewater injection, release of CH4, etc) while the impacts of these factors are being studied
b. Establishing error bars on input emissions data for environmental life cycle analysis and integrated assessment tools
c. Integrated impact assessment and prediction models that can accommodate a variety of data of different quality and scale – including qualitative measures where that’s as much as we may have, and data collected by civic/citizen scientists, also extending through sophisticated science/engineering techniques – that covers and combines data key to engineers, physical and social scientists, economists, regulators, and public for system evaluations
d. A framework for determining the appropriate tools used to manage subsurface risk (with tools that align with the continuum from high to low understanding)
5. **Whole systems** (2)
   
   a. How do we monitor the environment (whether baseline or operating) such that we can distill and constrain any meaningful parameter (i.e., representability/uncertainty)
   
   b. Energy systems analysis: what is the role of shale gas in the UK’s future energy portfolio? i.e., evidence base for choice between shale gas and other sources

6. **Wastewater** (3)
   
   a. What is happening to wastewater from oil and gas (conventional/unconventional); need tracking from cradle to grave for wastewater, including content and quantity

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C.1.2 **Longer term** *(within the next ten years)*

1. **Air emissions, air quality** (13)
   
   a. Understand emissions of VOCs due to shale oil vs. shale gas
   
   b. What are typical air emissions for oil and gas infrastructure?
   
   c. Role of unconventional gas in climate change/emissions agenda
   
   d. Air emissions from tanks, gathering lines, wastewater treatment facilities
   
   e. More global context of the detection and monitoring of methane concentrations in the atmosphere and the impact of hydrocarbons alongside other factors
   
   f. Determination of unusual gas emissions from long-term gas monitoring
   
   g. Is it possible to create a natural gas supply chain that emits less than 1% of methane produced?
   
   h. True impact on air quality including greenhouse effects ozone, PM, etc.
   
   i. What are the halogenated organics in the air around wells
   
   j. How does the natural gas development trajectory change climate change/CO2 and CH4 targets in the long term, especially if we are not reserve limited
   
   k. What would our CH4 emission look like in 10 years with and without mitigation in place?
   
   l. Causes of and mitigations for VOCs/NOx emissions from shale sites
   
   m. Research evaluating how factors impact air quality and the extent of impact in areas; relationship if any to water quality impact

2. **Health effects** (5)
   
   a. Public health baseline pre UGD and public health post-data; UGD production and wastewater disposal sites
   
   b. Determine “true”/actual impact of frack sites on local/regional scales – health monitoring, and “happiness” measurement – pre, during, and post hydraulic fracturing
   
   c. Can we identify causal relationships between hydraulic fracturing and changing water quality, air quality, human health?
   
   d. Health risk-based prioritization plan that considers full supply chain, to identify key pollutants to monitor (from which to develop health-based baseline and mitigation plans)
3. Socioeconomic/societal impacts (8)
   a. Impact to local economy and social changes with the infrastructures set up by hydraulic fracturing activities (particularly after the resource is depleted)
   b. What are long-term economic and community impacts of earthquakes and air quality emissions?
   c. The best techniques for limiting the impact of energy production whilst maximizing production
   d. Will hydraulic fracturing go forward in the UK without social license?
   e. What is our 10-year goal to accommodate world population growth with our economic control and user demand and environmental stability?
   f. Main issues underlying community-level concerns
   g. Can shale gas development be coupled with transition to low-carbon renewables?

4. System understanding (6)
   a. How does the coupled system of fluid flow, ground deformation (seismicity), chemicals and gases, work, and what length/time scales?
   b. What are the “consequential” impacts of increased unconventional?
   c. The consequences of unconventional oil and gas development of the national energy system, broadly defined
   d. Long-term well integrity issue post closure as it relates to GHG and air emissions, seismicity and connectivity to reservoirs, and risk to aquifers
   e. Comparing the picture 10 years on with possible baselines, what the (heck) happened?
   f. Developing systems-level models that can be used to understand/explore complex interactions between system components in the context of significant uncertainties

5. Data management/interpretation (3)
   a. Establish integrated database of management, seismicity, and air quality; an interdisciplinary approach
   b. Reliable data sets for input emissions that could be used to generate probability distributions
   c. Have industry make microseismic datasets available to the public after 5 years of collection

6. Regulatory, decision making (2)
   a. Study how industrial development risk management decisions are made by government organizations at local, regional, and national levels, and how this process can be improved (in democratic societies)
   b. How do we get the UK population to understand the contexts (e.g., what regulators do vs. what they wish) have the right impact on policy?

7. Perceptions, attitudes/behavior (2)
   a. In the long run, how do we change people’s perceptions toward this industry? To advertise more and educating them? Or maybe our knowledge is yet limited and that’s why we cannot convince them
   b. How do attitudes and behaviors change as progress from explanation (start, UK) to full-scale development (as in US)
8. **Water reuse** (4) *note this is a day 2 topic*

   a. Since in some places, disposal wells are the cheapest method of managing produced water, how can we encourage operators to recycle their produced water? Is there any need for further regulation?
   b. Optimal flowback/produced water management – reuse, recycling, disposal
   c. Gap: acceptance of produced water reuse
   d. Alternative disposal options to reduce produced water injection volumes, thereby reducing potential seismicity issues

C.2 Research priorities reported for Day 2 themes: Water availability and quality, wastewater treatment and disposal

C.2.1 Near Term *during the coming year*

1. Water treatment technologies
   a. Technologies for water treatment and sludge disposal
   b. Cost effective water treatment and reuse
   c. Best available techniques for wastewater recycling onsite
   d. Short term collaboration on water management and treatment to solve immediate needs
      - Social license and issues to move UK forward
   e. Scale of UK produced water problem
   f. Develop new technology to treat produced water economically and with flexibility for a variety of potential reuse options
   g. Enhance chemistry and water technology
   h. Development of integrated water treatment options that are cost effective and low carbon
   i. Management of produced water reuse/recycling disposal – tradeoffs and unintended consequences
   j. Technology options for treatment trains, storage, disposition (including reuse) customizable to formation geochemistry, and representative fracturing fluids- context for produced water quality

2. Characterization/ monitoring
   a. Improved characterization of produced waters to inform alternative management options in order to minimize potential risks
      - Methods development for saline water analysis
      - Improved organics analysis
      - Chemical reference materials to verify results
   b. Clear guidelines as to what needs to be measured in produced water flowback
   c. Determine the composition of flowback fluid in terms of formation water and injected water ratio
   d. What parameter should be measured as indicators of groundwater contamination from shale gas operations/hydraulic fracturing
   e. Better characterization of fluids (quantity, quality, source) for plays and consideration of data repository for sharing of data for researchers
   f. Evaluate the flowback and chemistry and the fate of injected fluids
g. Environmental chemistry of class II wells in the US
h. NORM in oil and gas wastewater

3. Current water impacts
   a. Improved understanding of most critical pathways to groundwater endangerment and best practices to avoid these
   b. Monitor water disposal sites completely with shallow and deep monitoring wells
   c. Increase intensity of water contamination studies in the US
   d. Seismicity signature from injection wells
   e. Potential linkages of fracture and flowback water into shallow aquifers and surface water
   f. What are the migration pathways for fluids from deep fractures to the surface (in addition to well failure)
   g. Develop improved understanding of wastewater and induced seismicity and how to avoid it
   h. Establishing a solid baseline of environmental water quality and all the things that affect it – quality analyses, vulnerability, faults, existing anthropogenic actors, etc.

4. Life-cycle analysis / systems analysis
   a. Full cost accounting of costs from lifecycle of shale production
      - Water cost to local ecosystem
      - Wastewater treatment (not just dilution)
      - Well casing to insure well integrity
      - Long-term monitoring post abandonment
   b. Comprehensive LCS for the overall water use/disposal that into account Life cycle costs as well
   c. Might the emergent long term cumulative environmental impacts (and cost to society) challenge the EIA’s optimism about future production growth
   d. Water management economics (viability of water management in UK context) as predicated on
      - Volume of produced fluids
      - Treatment requirements
      - Disposal requirements

5. Miscellaneous
   a. Collection infrastructure to collect methane (Bakken)

C.2.2 Longer term (within the next ten years)

1. Water treatment management technologies
   a. New technologies/science to develop long-term needs
   b. International set of water reuse treatment guidelines /standards
   c. Improved systems modeling /assessment of process water reuse/wastewater management
   d. Status of water treatment technologies
   e. Cost-effective water treatment technology
   f. Need cost-effective and sustainable system for managing waste water
   g. Membrane process development for salt removal for oil/gas wastewaters to develop cost effective desalination
h. More effective and economical desalination technologies
i. Improved produced water management and disposal
j. Treatment/disposal of high TDS water
k. Advanced efficient treatment technology for saline waters (e.g. biological treatment?)

2. Net benefit/risk
   a. Risk Evaluation of shale gas hydraulic fracturing including exposure pathways and long-term behavior
   b. Life cycle analyses – environmental/health impacts and costs, including (in particular) associated with reuse and wastewater disposal – for consideration with other energy options in “all of the above” portfolio
   c. Develop quantitative risk assessment and management tools (with supporting data) to inform decision making
   d. Whole life risk and costs
   e. Full cost accounting from alternative energy sources (lifecycle costs)
      - Shale
      - Other oil and gas
      - Wind
   f. Update regulation on conventional oil and gas to more easily characterize and separate effects
   g. Net economic benefit of shale oil and gas production

3. Monitoring/characterization
   a. Solids characterization including NORM/TENORM for understanding health risk for operators, transports and disposal facilities
   b. Mapping of the water table – potable water/saline waters
   c. Time lapse 4D imaging of water production and flow
   d. Can you link real-time microseismic monitoring to reduce water production during fracturing (i.e. stay in producing zone rather than adjacent water bearing formations)
   e. Monitoring of groundwater and surface waters
      - Develop cost—effective standardized methods
      - Can we repurpose existing networks?

4. Integrated water management
   a. Best available technologies for reducing volume of water required for hydraulic fracturing
   b. Standardize hydrofracturing practices for better management of produced water
   c. The need for an integrated water management strategy/solution in the UK (based on learning from US experiences)
   d. Integrated water management to achieve sustainable water management

5. Miscellaneous
   a. Geomechanical response of water injection and production
   b. Well construction to prevent migration of natural gas and fracture fluids
   c. What is the legacy impact of hydraulic fracturing on the subsurface environment (e.g. biology changes) and how long might impacts be felt in groundwater reservoirs
## Table D.1 Workshop Participants

<table>
<thead>
<tr>
<th>United States</th>
<th>United Kingdom</th>
</tr>
</thead>
<tbody>
<tr>
<td>David Allen, University of Texas</td>
<td>Matthew Agarwala, University of East Anglia</td>
</tr>
<tr>
<td>Susan Christopherson, Cornell University</td>
<td>Grant Allen, University of Manchester</td>
</tr>
<tr>
<td>Corrie Clark, DOE Argonne National Lab</td>
<td>Clare Bond, University of Aberdeen</td>
</tr>
<tr>
<td><strong>Bill Cooper, National Science Foundation</strong></td>
<td></td>
</tr>
<tr>
<td>Robert Dilmore, DOE National Energy Technology Lab</td>
<td>Neil Burnside, University of Glasgow</td>
</tr>
<tr>
<td>David Dzombak, Carnegie Mellon University</td>
<td>Frederic Coulon, Cranfield University</td>
</tr>
<tr>
<td>Will Fleckenstein, Colorado School of Mines</td>
<td><strong>Richard Davies, Newcastle University</strong> *</td>
</tr>
<tr>
<td>Davis Ford, Davis Ford, Associates</td>
<td>Pete Edwards, NERC National Center for Atmospheric Science</td>
</tr>
<tr>
<td>Shanti Gamper-Rabindran, University of Pitts</td>
<td><strong>Steve Elsby, Research Councils UK</strong></td>
</tr>
<tr>
<td>Mike Griffin, Carnegie Mellon University</td>
<td>Matthew Hall, University of Nottingham</td>
</tr>
<tr>
<td><strong>Bruce Hamilton, National Science Foundation</strong></td>
<td>Geoffery Hammond, University of Bath</td>
</tr>
<tr>
<td>Rich Haut, Houston Advanced Research Center</td>
<td>Alywn Hart, UK Environment Agency</td>
</tr>
<tr>
<td>Jeffrey Jacquet, South Dakota State University</td>
<td>Adam Hawkes, Imperial College London</td>
</tr>
<tr>
<td>Margaret MacDonell, DOE Argonne National Lab</td>
<td>Mike Kendall, University of Bristol</td>
</tr>
<tr>
<td>Meagan Mauter, Carnegie Mellon University</td>
<td><strong>Sarah Keynes, NERC Innovation</strong></td>
</tr>
<tr>
<td>Chong Na, Texas Tech University</td>
<td>James Rose, UK Department of Energy &amp; Climate Change</td>
</tr>
<tr>
<td>Jon Olson, University of Texas</td>
<td>Steve Thompsett, UK Onshore Oil and Gas</td>
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<tr>
<td><strong>Danny Reible, Texas Tech University</strong> *</td>
<td>Rob Ward, British Geological Survey</td>
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<td>Mitchell Small, Carnegie Mellon University</td>
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An asterisk indicates the co-lead organizers, and bold font indicates further contributors.