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

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Arlington, Virginia, USA

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ACRONYMS AND ABBREVIATIONS

BB	broad band
CBM	coalbed methane
CH_4	methane
CO_2	carbon dioxide
EA	Environment Agency (England)
EU	European Union
GHG	greenhouse gas(es)
HC	hydrocarbon
HF	hydraulic fracturing
LCA	life-cycle assessment
LCC	life-cycle cost(s)
LCS	life-cycle system(s)
NERC	Natural Environment Research Council
NOx	nitrogen oxides
NORM	naturally occurring radioactive material
NSF	National Science Foundation
PM	particulate matter
RCUK	Research Councils UK
RRC	Railroad Commission (regulatory agency in Texas)
SP	short period (seismicity sensors)
TDS	total dissolved solids
UCG	underground coal gasification
UK	United Kingdom
US	United States
VOC	volatile organic compound(s)

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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.

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 2.2 Presentation Highlights

	Presenters per Session	Status and Perspectives	Knowledge Gaps, Research Needs and Translation Opportunities
I	**Whole-systems approach**		
US	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
UK	Matthew Agarwala *(University of East Anglia)*	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
	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 *(University of Bristol)*	• Lack of wastewater injection limits sources of induced seismicity • Mining has been linked to induced seismicity in UK • First fracturing well led to seismic events	• Can maximum magnitude be forecast? • What is needed for baseline monitoring? • Setting appropriate threshold for red light monitoring? • 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	• Improve options for reuse by understanding quality requirements and improving chemical additives to overcome quality constraints

		• Eventually reuse demand will cease	• 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 CH_4 through the extraction process and other stages in the life cycle as well as CO_2 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 permanantly 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 CO_2 and hydrocarbon gases. The use of CO_2 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 $CO_2$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 1000m 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 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 an 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

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

4.2

Waste Water	**Prediction of the volumes of waste water that could be produced.** **Cost effective treatment technologies in the absence of deep well disposal.**	**UK/US**	**Deep well disposal not currently an option in the UK. Lack of appropriate disposal options could cause the UK shale industry to be uneconomic.** **Although deep well disposal is commonly used in the US in some states, it is not always available and cost-effective and efficient treatment technologies are also of interest in the US.**
Waste Water Management	**Understanding fate and pathway of fluids over time after spills and leaks.** **Understanding seismicity and relationship to injection.**	**Both** **USA**	**Greater processing of waste waters may lead to greater likelihood of spills and leaks.** **Increasing number of earthquakes > M4.4 in the US due to waste water injection.**
Hydraulic Fracturing Induced Seismicity	**Prediction of maximum potential earthquake.** **Improvement in measurement technology.**	**Both**	**Earthquakes have been less than M4.4 in US, UK max 2.3 M. A matter of public concern but impact moderate to low.**

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.

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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

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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

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)

   <u>Super-emitters</u> (3)
   a. Locate super-emitters of CH_4 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

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, an d 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 reus**e (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 tom 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

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APPENDIX D: PARTICIPANTS

Table D.1 Workshop Participants

United States	United Kingdom
David Allen, University of Texas	Matthew Agarwala, University of East Anglia
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Jon Olson, University of Texas	Steve Thompsett, UK Onshore Oil and Gas
Danny Reible, Texas Tech University*	Rob Ward, British Geological Survey
Nino Ripepi, Virginia Tech University	Fred Worrall, University of Durham
Nichole Saunders, Environmental Defense Fund	**Blanche Wynn-Jones, NERC Science**
Bridget Scanlon, University of Texas (BEG)	
Mitchell Small, Carnegie Mellon University	
Gene Theodori, Sam Houston State University	
Lashun Thomas, University of Arkansas-Little Rock	
Avner Vengosh, Duke University	
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An asterisk indicates the co-lead organizers, and bold font indicates further contributors.