Public Health England

Review of the Potential Public Health Impacts of Exposures to Chemical and Radioactive Pollutants as a Result of the Shale Gas Extraction Process

About Public Health England

Public Health England's mission is to protect and improve the nation's health and to address inequalities through working with national and local government, the NHS, industry and the voluntary and community sector. PHE is an operationally autonomous executive agency of the Department of Health.

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Review of the Potential Public Health Impacts of Exposures to Chemical and Radioactive Pollutants as a Result of the Shale Gas Extraction Process

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This report provides Public Health England advice on the potential public health impacts of exposures to chemical and radioactive pollutants as a result of shale gas extraction. There have been no significant changes to the findings in the draft report, PHE-CRCE-002, which was published for comment in October 2013.

The report has been updated in the light of new significant scientific evidence in peer reviewed or published reports, up to January 2014.

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This report from the PHE Centre for Radiation, Chemical and Environmental Hazards reflects understanding and evaluation of the current scientific evidence as presented and referenced in this document.

EXECUTIVE SUMMARY

Public Health England (PHE) is an executive agency of the Department of Health and provides a nationwide, integrated public health service, supporting people to make healthier choices. PHE aims to ensure that everyone is protected from threats to their health from infectious disease and environmental hazards. PHE has operational autonomy and is free to publish or speak on issues relating to the nation's health and wellbeing in order to set out professional, scientific and objective judgements of the evidence base.

Shale gas extraction is at an early exploratory stage in the UK with very limited drilling having actually occurred. Indeed, fracturing operations to test for shale gas extraction in the UK have only occurred at one site to date and that was halted following minor earth tremors. It is likely that further exploratory drilling will commence soon. Despite such limited activity to date, shale gas extraction raises concerns with the general public. Well publicised reports from other countries, most notably the US, suggest that drilling and extraction of shale gas using hydraulic fracturing, commonly referred to as fracking, has the potential to adversely impact the environment and human health.

In response to emerging public concern regarding the process of hydraulic fracturing for shale gas extraction, and requests for advice from national and local agencies, the PHE Centre for Radiation, Chemical and Environmental Hazards (CRCE) has reviewed the potential public health impact of direct emissions of chemicals and radioactive material from the extraction of shale gas. Other considerations such as climate change and greenhouse gas emissions, sustainable use of water resources, nuisance issues such as noise and odours, traffic (apart from vehicle exhaust emissions), occupational health, and visual impact, are not considered in this review. Similarly, the review does not consider the socioeconomic benefits or impacts of shale gas extraction.

This review focuses on the potential public health impacts of exposures to chemical and radiological pollutants as a result of shale gas extraction in the UK, based on the examination of literature and data from countries which already have commercial-scale shale gas extraction operations. Caution is required when extrapolating experiences in other countries to the UK since the mode of operation, underlying geology and regulatory environment are likely to be different.

An assessment of the currently available evidence indicates that the potential risks to public health from exposure to the emissions associated with shale gas extraction will be low if the operations are properly run and regulated. Most evidence suggests that contamination of groundwater, if it occurs, is most likely to be caused by leakage through the vertical borehole. Contamination of groundwater from the underground hydraulic fracturing process itself (ie the fracturing of the shale) is unlikely. However, surface spills of hydraulic fracturing fluids or wastewater may affect groundwater, and emissions to air also have the potential to impact on health.

Where potential risks have been identified in the literature, the reported problems are typically a result of operational failure and a poor regulatory environment. Therefore, good on-site management and appropriate regulation of all aspects including exploratory drilling, gas capture, use and storage of hydraulic fracturing fluid, and post-operations decommissioning are essential to minimise the risk to the environment and public health. In the UK, shale gas

developers and operators will be required, through the planning and environmental permitting processes, to satisfy the relevant regulators that their proposals and operations will minimise the potential for pollution and risks to public health. PHE and other public health bodies will provide support by responding to requests to assess the potential impact on health in specific circumstances.

The risks from small-scale drilling for exploratory purposes (eg single wells) are clearly different from the risks from commercial-scale operations. The potential health impact from single wells is likely to be very small, but the cumulative impacts of many wells in various phases of development in relatively small areas are potentially greater and will need careful scrutiny, during the planning process.

A few studies have suggested associations between adverse health impacts and shale gas extraction activities; however, the authors highlighted study limitations and it is evident that further work is required. The UK has the opportunity in advance of significant development of shale gas extraction activities to consider appropriate environmental and epidemiological studies to extend and strengthen the evidence base on potential health impacts from shale gas extraction emissions.

The report makes a number of recommendations:

- **a** Public Health England needs to continue to work with regulators to ensure all aspects of shale gas extraction and related activities are properly risk assessed as part of the planning and permitting process
- **b** Baseline environmental monitoring is needed to facilitate the assessment of the impact of shale gas extraction on the environment and public health. There should also be consideration of the development of emission inventories as part of the regulatory regime
- **c** Effective environmental monitoring in the vicinity of shale gas extraction sites is needed throughout the lifetime of development, production and post-production
- **d** It is important to ensure that broader public health and socioeconomic impacts such as increased traffic, impacts on local infrastructure and worker migration are considered
- **e** Chemicals used in hydraulic fracturing fluid should be publicly disclosed and risk assessed prior to use. It is useful to note that any potential risk to public health and the environment from hydraulic fracturing chemicals will be dependent on the route of exposure, total amount and concentration, and eventual fate of any such chemicals. It is expected that these aspects will be considered as part of the regulatory environmental permitting process
- **f** The type and composition of the gas extracted is likely to vary depending on the underlying geology and this necessitates each site to be assessed on a case-by-case basis
- **g** Evidence from the US suggests that the maintenance of well integrity, including post-operations, and appropriate storage and management of hydraulic fracturing fluids and wastes are important factors in controlling risks and appropriate regulatory control is needed
- **h** Characterisation of potentially mobilised natural contaminants is needed including naturally occurring radioactive materials (NORM) and dissolved minerals

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1 INTRODUCTION

Shale gas is a natural gas found in a commonly occurring, fine grained sedimentary rock known as shale. The extraction or production of natural gas from shale differs from conventional forms of gas and oil extraction from defined reservoirs or traps where the hydrocarbon (the gas or oil) has migrated from the source rock. In the case of shale gas, the extraction is considered unconventional as the gas is obtained directly from the source rock itself.

Shale gas is typically methane but may contain small quantities of other gases including hydrogen sulphide, carbon dioxide, nitrogen and other hydrocarbons. The composition of shale gas is dependent on the geological formation as well as the temperature and pressure that the formation has been subjected to over time.

To extract shale gas, the usual approach involves the drilling of a number of wells in different directions (called directional drilling) from a single well pad to target potential reserves of gas, which is illustrated below (Figure 1).

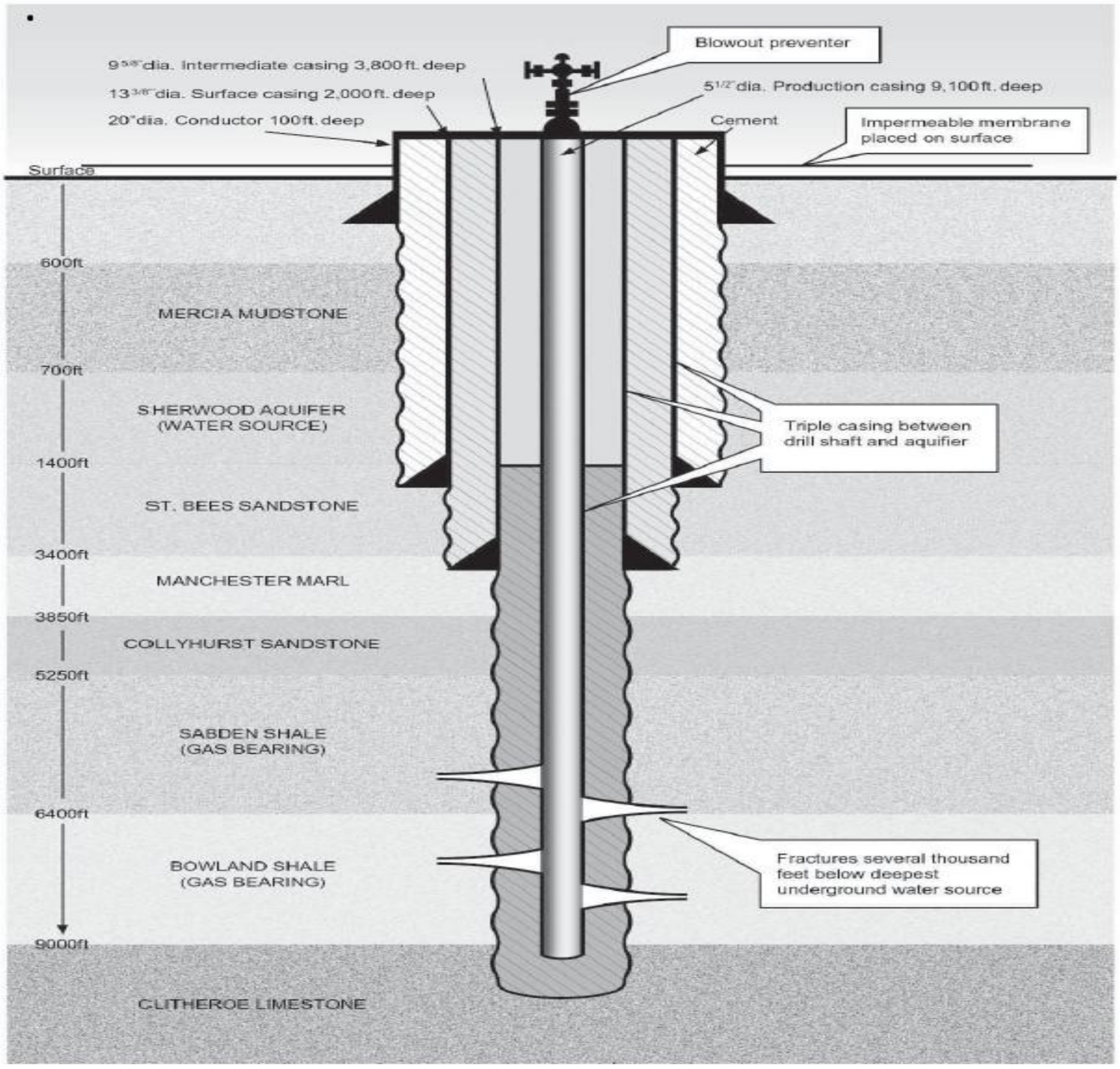

FIGURE 1 Bowland shale well schematic (not to scale)
Source: http://www.publications.parliament.uk/pa/cm201012/cmselect/cmenergy/795/795we09.htm

The initial step is the drilling of a vertical borehole to a prescribed depth. Once the final vertical depth has been reached the core of the borehole is encased with cement to prevent contamination of the surrounding rock. Horizontal directional drilling of the rock may take place in different directions and these horizontal drillings can extend for thousands of metres from the original vertical borehole. In order to extract gas from the shale, a process called hydraulic fracturing, also known as fracking is used. This is a technique in which water is pumped into the rock at high pressures to create small fractures or cracks in the shale. These fractures allow the gas to escape from the shale and flow into the well bore where it is carried back to the surface for capture and processing. Once the fractures are created, small particles, typically grains of sand, are used to keep the fractures open (called proppants or propping agents). Chemicals are often added to the water to improve the efficiency of the fracturing process and these include friction reducers, surfactants, gelling agents, scale inhibitors, acids, corrosion inhibitors, antibacterial agents and clay stabilisers. This mixture is termed hydraulic fracturing fluid and the fracturing process can involve the use of large quantities of this fluid, with estimates ranging from 9,000 to 29,000 m^3 (9–29 million litres) water per well, which is usually made up on-site from water supplied from the local water company or abstracted from a local water course or aquifer.

A significant proportion of the hydraulic fracturing fluid pumped into the borehole is lost below ground; however, some fluid, known as flowback water, returns to the surface. The flowback water is returned to the surface as a high pressure mixture of natural gas (predominantly methane), other gases, water, brine, solids, minerals and hydrocarbons. It may also contain low levels of naturally occurring radioactive materials (NORM). Estimates of the fraction of flowback water recovered varies by geologic formation and typically ranges from 10% to 70% of the injected hydraulic fracturing fluid (Ground Water Protection Council and ALL Consulting, 2009; US EPA, 2011). The volume of flowback water depends on the properties of the shale, the fracturing design and the type of hydraulic fracturing fluid used (King, 2012).

The shale gases are separated out while the flowback water and hydrocarbons are stored on-site in storage tanks. The hydrocarbon liquid is called condensate and can be transported to refineries for further processing.

Drilling and extracting shale gas, whether for exploratory or commercial purposes, broadly involves five separate stages:

- **a** Developing a well pad and drilling and constructing a wellbore to the target shale formation. This can involve horizontal drilling in a number of directions
- **b** Hydraulic fracturing of the shale to extract the gas
- **c** Capture and processing of the returning gas (during the exploratory phase this may involve flaring or venting of the gas)
- **d** Storage, treatment and disposal of flowback water and other wastes
- **e** Decommissioning of the borehole and well pad

Gas exploration techniques, using directional drilling and hydraulic fracturing, are not new and have been used across the oil and gas industry (including in the UK) for many decades. As the technology has improved over time so has the ability to exploit shale gas economically, through the use of hydraulic fracturing.

There is little practical experience of shale gas exploration in the UK. The Environment Agency (EA) has published an environmental risk assessment (ERA) for the exploratory phase of development to document the main environmental risks (EA, 2013a). The ERA covers a number of areas including chemical mixing, borehole integrity, well injection, management of flowback fluid and gas, waste disposal and well decommissioning.

To aid the ERA a conceptual model of the potential emissions and pathways of exposure from a single well and borehole was produced (Figure 2).

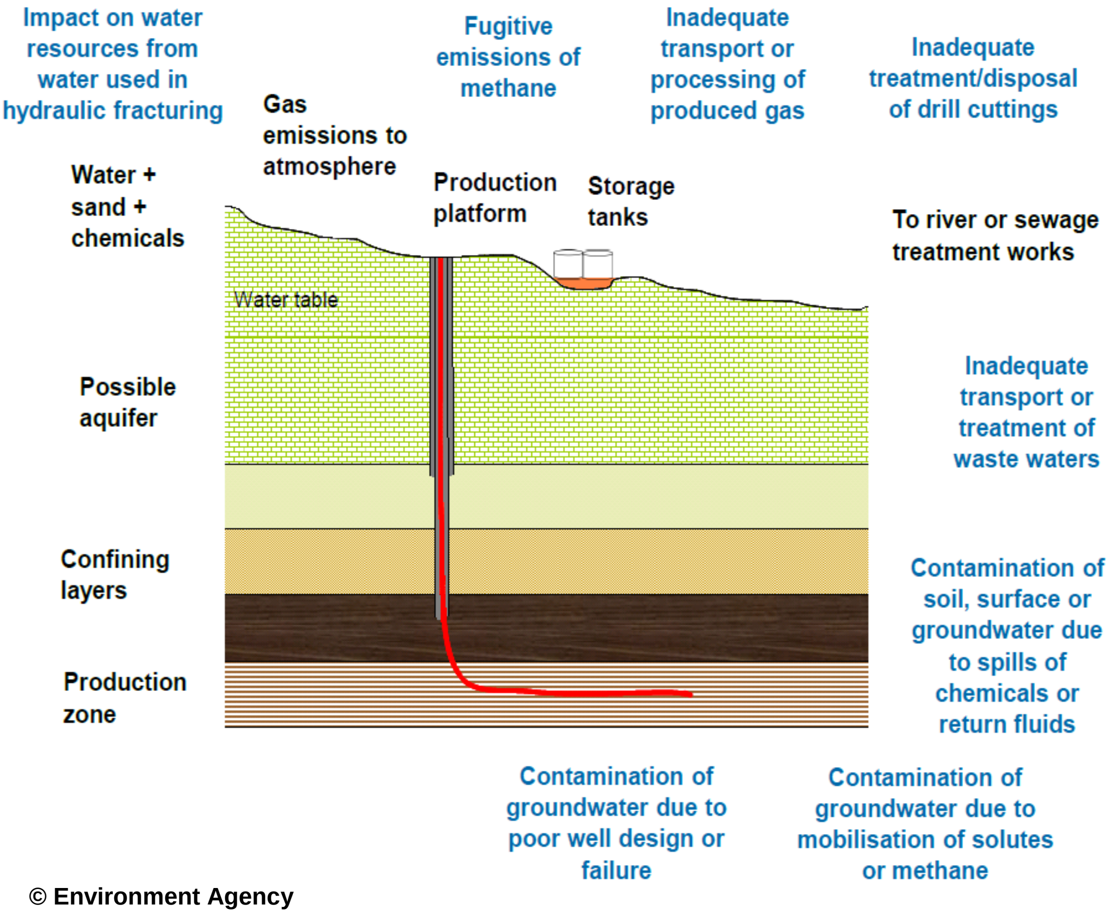

FIGURE 2 Environmental risks of shale gas extraction (EA, 2013a)

It has been proposed that the exploitation of shale gas resources has the potential to provide economic and environmental benefits (IOD, 2013; US EPA, 2013); however, this remains subject to debate. Experience from other countries, especially the US, suggests that shale gas has the potential to be a widely distributed resource that can be relatively cheaply produced and may lessen dependence on imported oil and gas, which has important energy security benefits. The development of shale gas in the US has been very rapid. In 2001 shale gas was less than 2% of the total US natural gas production; in 2011 it approached 30% (Secretary of Energy Advisory Board, 2011). The US Energy Information Administration is predicting a continuing expansion of shale gas production in the future and projects that shale gas will account for 46% of domestic production by 2035 (US EIA, 2011).

The scale of future shale gas production in the UK remains uncertain. The British Geological Survey (BGS) has undertaken the carboniferous Bowland Shale study (BGS, 2013) which estimated 1,300 trillion cubic feet of ‘gas in place’. Other areas with potential shale gas or oil deposits include the Weald Basin in Surrey and Sussex, parts of the midlands and the central belt of Scotland. There is little information on the amount of gas that may be technically recoverable in shale beds in the UK. Further work continues by the BGS to assess the UK's shale gas resources.

The Department of Energy and Climate Change (DECC) has commissioned a strategic environmental assessment (SEA) on proposals for further onshore oil and gas licensing in areas of the Great Britain. The SEA aims to identify, describe and evaluate the likely significant environmental effects of further onshore oil and gas licensing in order to comply with the requirements of the European Strategic Environmental Assessment Directive (2001/42/EC) (AMEC, 2013).

The SEA considers all the stages in the oil and gas production and development lifecycle, under high and low activity scenarios, for both conventional and unconventional oil and gas. The low and high activity scenarios for unconventional gas include the following assumptions: between 50 and 150 licences being awarded; 30 and 120 well pads being developed (each having between 6 and 24 wells and occupying 3 hectares of land); peak number of wells drilled in a year of 360 and a maximum of 2,880 wells drilled, production of 85.6 million m^3 of gas (3 billion cubic feet) per well; and a lifetime of each well assumed to be 20 years.

The SEA identifies potentially significant effects for either shale oil or gas production, compared to the existing oil and gas sector, or at the local community level. In the high activity scenario potentially positive benefits may include increased UK hydrocarbon reserves and levels of employment as well as financial contributions to local communities, while potentially negative impacts include increased wastewater production placing a burden on existing wastewater treatment capacity, increased traffic and impacts on congestion, noise and air quality, as well as potentially increased greenhouse gas emissions. These impacts apply during the development and production phases although the industry is not expected to be at a substantial scale until the 2020s, which should allow time for any new investment in infrastructure capacity such as wastewater treatment works. The SEA also notes the importance of applying and enforcing regulatory requirements to ensure that any significant effects at the project level will be identified, assessed and mitigated to an acceptable level (AMEC, 2013). Across Europe there is considerable interest in developing shale gas resources, with Poland, Germany, the Netherlands, Spain, Romania, Lithuania, Denmark, Sweden and Hungary all expressing an interest (AEA Technology, 2012a).

The impacts of shale and other forms of unconventional gas extraction have also been subject to a number of independent reviews in the UK, including by the Tyndall Centre for Climate Change Research (Broderick et al, 2011), the House of Commons Energy and Climate Change Committee (House of Commons, 2011) and, most recently, The Royal Society and The Royal Academy of Engineering (RS and RAE, 2012). All three reviews concluded that there are potential health and environmental impacts associated with shale gas extraction. The main risks were identified as potential contamination of the environment, with hydraulic fracturing fluids or natural contaminants mobilised as a result of the fracturing process. The need for appropriate regulation of all aspects of shale gas extraction was also recognised, with key recommendations including the need for risk assessment of the chemicals used in hydraulic fracturing fluids and ensuring good design and integrity of wells. Environmental monitoring before, during and after hydraulic fracturing and improved analytical techniques to detect the chemicals in hydraulic fracturing fluid and flowback water were also recommended.

Outside the UK, there have been a number of reviews and studies for the European Commission covering environmental, health and climate change impacts (AEA Technology, 2012a,b: European Parliament, 2011), a comprehensive health impact assessment in the US (Colorado School of Public Health, 2011) and a detailed examination of the potential public health impacts in New Brunswick, Canada (Office of the Chief Medical Officer of Health, 2012). The United States Environmental Protection Agency (US EPA) is currently conducting a detailed study into the potential impacts of hydraulic fracturing on drinking water and ground water, which is due for publication in 2014 (US EPA, 2013).

As with any industrial process, shale gas extraction must be undertaken in a manner that reduces the impact on the environment and consequently minimises the risk to human health.

In the US, public concern about shale gas extraction has grown as production has increased and typically falls into five areas:

a Pollution of drinking water supplies

b Air pollution

c Community disruption during shale gas production

d Supply and safe storage of chemicals used in hydraulic fracturing

e Cumulative adverse impact on communities

Similar concerns have been raised about shale gas extraction in the UK in advance of commercial drilling. In addition to the areas identified above, other potential concerns may include:

f Radionuclides dissolved in water, including NORM and radon, which can be released underground from rocks and become dissolved in the hydraulic fracturing fluid

g Radioactive tracers if they are used to monitor the hydraulic fracturing process (IAEA, 2003)

h Contamination arising from wastewater

2 SCOPE AND PROCEDURE

A search of the published or peer reviewed scientific literature until January 2014 was undertaken. The search strategy initially aimed to capture the widest number of publications as possible. Searches for peer reviewed papers were carried out over the following databases: Toxnet, Scopus and PubMed.

The initial search strategy used the following terms across all fields ‘hydraulic fracturing’ OR ‘hydraulic fracturing fluids’ OR ‘shale gas development’ OR ‘shale gas’ OR ‘shale gas extraction’ OR ‘shale gas drilling’ OR ‘shale gas exploration’ OR ‘shale gas production’ OR ‘shale gas industry’ OR ‘unconventional gas’ OR ‘unconventional gas extraction’ AND ‘health’. The initial search returned 1276 references, duplicates were removed and the reference titles were subsequently scanned and articles outside the scope of the review were eliminated.

The screening resulted in a total of 303 references, which were then subject to further review of titles, keywords, abstracts and full text where these were available. The review focused on references in the English language and consideration of human health impacts. A number of further papers were excluded based on the scope of the review, such as those relating to impacts on climate change or energy policy, as well as conference proceedings and papers related to offshore exploration.

Further literature was identified from internet searches and key government websites in the UK, European Union, US and Canada. The titles and keywords of relevant papers were scanned to select the best words/phrases to refine the search. Search terms used included shale gas, hydraulic fracturing fluid, hydraulic fracturing, fracking, fracturing, unconventional gas, NORM, radon, frack and radioactive.

Contacts were also made in the UK with a range of stakeholders including the Environment Agency, British Geological Survey and the Department of Energy and Climate Change (DECC).

All the references were assessed by a working group of the report authors, with the greatest weighting given to reports and papers published in the scientific literature especially peer reviewed papers. The reviewers carefully assessed the literature in an attempt to avoid publications with potential conflicts of interest. Anecdotal evidence from websites and social media were not included unless cited in published reports. The majority of the literature did not relate directly to health and the final report considered 229 papers or reports, 110 of which are directly cited.

This report is focused exclusively on the direct health impact of releases into the environment due to emissions from the production of shale gas (and some liquid hydrocarbons) from shale formations with hydraulic fracturing in either vertical or horizontal wells.

For the purposes of this report, the following areas have been considered:

a Air pollution including from stationary on-site sources, and radon

b Water pollution including the use of hydraulic fracturing fluids, flowback water, presence of natural substances, eg heavy metals and NORM, and the risk to watercourses or aquifers

c Land/waste issues including disposal and treatment of wastewater, muds, etc

The following areas are outside the scope of this report:

a Occupational health issues

b Water usage and water sustainability issues

c Energy policy and security

d Nuisance issues including, noise and odours

e Seismicity

f Wider impacts of shale gas extraction on local employment and the local economy

g Detailed consideration of the longer-term impact of shale gas extraction on climate change

It is recognised that community concerns can extend to broader issues (eg socioeconomic impacts, visual amenity and noise) and there is a wider public debate about the longer-term impact of shale gas extraction on greenhouse gas emissions and their impact on climate change. It is also recognised that some of the observations and recommendations in this report could be extended to other oil and gas operations. However, this assessment has focused solely on issues related to local emissions arising from shale gas extraction and any potential direct health impacts.

The impacts on climate change have not been addressed in this review; however, climate change remains an area of concern for public health and must be considered in any strategic decisions related to the energy industry. The impacts of shale gas extraction on climate change have been considered in reviews by DECC (MacKay and Stone, 2013) and by the Tyndall Centre for Climate Change Research (Broderick et al, 2011) as well as the European Commission (AEA Technology, 2012b) and the United Nations Environment Programme (UNEP) (Peduzzi and Harding, 2013).

3 REGULATORY ENVIRONMENT

In the UK robust regulatory requirements governing onshore oil and gas exploration already exist and shale gas extraction will be regulated within this framework. The UK has a goal-setting approach to regulation that requires operators to ensure and demonstrate to regulators that the risks of an incident relating to oil and gas operations are reduced to ‘as low as reasonably practicable’. The aim is to encourage operators to move beyond minimum standards in a continuous effort for improvement (DECC, 2013). The EU has recommended that member states ensure that companies apply best available techniques (BAT), where applicable, and good industry practices to prevent, manage and reduce the impacts and risks associated with exploration and production projects. Industry should strive for maximum transparency in its operations and constantly improve technologies and operating practices.

The DECC Office of Unconventional Gas and Oil (OUGO) has published a regulatory roadmap for onshore oil and gas exploration. The roadmap details the licensing, permitting and permissions process for onshore oil and gas exploration, including shale gas, and covers the exploration and appraisal phases of onshore oil and gas exploration (DECC, 2013).

DECC (Department of Enterprise, Trade, and Investment (DETI) in Northern Ireland) issues a licence that grants exclusivity to operators in the licence area to explore for and produce petroleum. Operators must negotiate access with the relevant landowner and also seek planning permission from the local minerals planning authority (MPA), the local planning authority (LPA) if in Scotland, or DOE Planning if in Northern Ireland. Where a well may encroach upon coal seams, permission must also be sought from the Coal Authority (DECC, 2013).

The EA has published draft technical guidance for onshore oil and gas exploratory operations (EA, 2013b). The draft technical guidance has been produced to clarify which environmental regulations apply to the onshore oil and gas exploration sector and what operators need to do to comply with those regulations.

Environmental agencies are responsible for maintaining or improving the quality of surface water and groundwater. In relation to shale gas extraction and related activities this will be through the issue of environmental permits and consents, offering pollution prevention advice and conducting compliance activities.

3.1 Planning

Planning permission is required before any activity may start on a site. Operators apply to the relevant MPA for planning permission (the county council or unitary authority in England, or the planning authority in Scotland and Wales, or DOE Planning Service in Northern Ireland).

Separate planning permission is required for each stage of the development process (exploration, appraisal and production).

The planning system should ensure that new development is appropriate for its location, taking account of the effects (including cumulative effects) of pollution on health, the natural environment or general amenity and the potential sensitivity of the proposed area or development to adverse effects from pollution (DCLG, 2013).

The planning authority will consider economic, social, health and environmental factors as part of the decision-making process. If significant environmental impacts are likely, the planning authority will require the operator to develop an environmental statement as part of the environmental impact process on the potential risks to people, plants, animals, soil, water, climate, the landscape, architectural and archaeological heritage, and others, as well as how they can be mitigated (DECC, 2013).

3.2 Environmental impact assessment (EIA)

As part of the planning permission process, the MPA/LPA/DOE will determine if an EIA is required. The Town & Country Planning (Environmental Impact Assessment) Regulations 2011, the Town & Country Planning (Environmental Impact Assessment) Regulations (England and Wales) 1999 (in Wales), the Town & Country Planning (Environmental Impact Assessment) (Scotland) Regulations 2011 and the Planning (Environmental Impact Assessment) Regulations (NI) 2012 set out the process for determining whether or not an EIA is required. An EIA is mandatory for projects listed in Schedule 1. Schedule 2 projects are screened to assess whether an EIA is required.

Unconventional gas exploration and exploitation will not always fall within Schedule 1 activities as these are more likely to apply at the extraction/production stage when production capacities of a well are more likely to be known. It is most likely therefore that shale gas drilling operations for exploration would fall within Schedule 2 (EA, 2013b), which includes the following relevant categories:

a Deep drilling where the area of the works exceeds 1 hectare

b Surface industrial installations for the extraction of coal, petroleum, natural gas and ores, as well as bituminous shale, where the area of the development exceeds 0.5 hectare

c Industrial installations for carrying gas where the area of the works exceeds 1 hectare

d Surface storage of natural gas where the area of any new building, deposit or structure exceeds 500 m^2 or a new building, deposit or structure is to be sited within 100 m of any controlled waters

If the development falls within the criteria set out in Schedule 2 or is located in a sensitive area, the development may be screened to assess whether or not it is likely to have significant effects on the environment and thus whether an EIA is required. An EIA is therefore not mandatory at the exploration phase and will depend on the assessment of whether there are likely to be significant effects on the environment from the exploration phase by virtue of factors such as the nature, size or location of the well to be drilled (DECC, 2013).

An industry body, the UK Onshore Operators Group (UKOOG), has stated that an EIA will be carried out for all exploration wells that involve hydraulic fracturing and that the scope of the environmental statement should be agreed with the planning authority. The operator will also carry out pre-application consultation on the EIA and proposed development with the local community. Following community engagement, the operator will submit an environmental statement (ES), setting out the details of the likely significant impacts on the environment agreed at the scoping stage, to the local planning authority as part of the overall planning application (UKOOG, 2013a).

3.3 Environmental permitting

An operator must consult the relevant environmental regulator: the Environment Agency (EA) in England, Natural Resources Wales (NRW) in Wales, the Scottish Environment Protection Agency (SEPA) in Scotland or the Northern Ireland Environment Agency (NIEA) in Northern Ireland, who are also statutory consultees to the MPA/LPA/DOE.

Environmental permits from the appropriate environmental regulator will be required for any borehole drilling as well as hydraulic fracturing activities and, in England, shale gas developments could require several permits under the Environmental Permitting (England and Wales) Regulations 2010, which incorporate the requirements of a number of different pieces of legislation, such as the Water Framework Directive, the Groundwater Daughter Directive and the Radioactive Substances Act 1993*. Environmental permits would cover areas such as water abstraction, groundwater activity, wastewater discharge consents, naturally occurring radioactive materials (NORM) and the handling and disposal of mining wastes. Exposure to radioactivity due to shale gas extraction will have to be assessed as part of this regulatory regime and radiation doses to members of the public will need to be demonstrated to be kept well below the statutory limit of 1 mSv (millisievert) a year. Environmental permits will only be issued if the relevant agency is confident that there is no unacceptable impact to the environment and, as part of this process, operators are required to disclose the content of hydraulic fracturing fluids to the relevant environmental regulator (DECC, 2013).

3.4 Health and safety

The Health and Safety Executive (HSE) will oversee working practices under the Health and Safety at Work Act 1974. The HSE is also responsible for regulating public safety within, and in the direct vicinity of, the well (borehole) work activities. In addition, the HSE is involved in ensuring well casing integrity and quality. HSE regulations require an independent and competent person to examine the well design and construction. The HSE must be notified of the well design and operation plans at least 21 days prior to drilling. The HSE will inspect the well design to ensure that measures are in place to control major hazards. Operators must also notify the environmental regulator of their intention to drill and the operators must meet all baseline monitoring requirements set out in planning permission and environmental permits before drilling can begin.

The HSE monitors well operations and will review weekly operations reports it receives from the well operator. The HSE intends to jointly inspect drilling and hydraulic fracturing operations with the relevant environmental regulator during the exploratory phase of shale gas extraction. HSE inspectors can visit any site at any time if there is a matter of concern.

* Similar provisions exist in other parts of the UK.

The relevant environmental regulator will monitor the environmental impacts and inspect the operator's reports: the greater the potential risk, the greater the scrutiny by environmental regulators. Conditions attached to permits will give the minimum level of site-based monitoring and reporting. Planning authorities are responsible for enforcing any conditions attached to the planning permission, such as monitoring of noise or dust levels.

The UK Onshore Operators Group (UKOOG) has produced guidelines for operators on well integrity and hydraulic fracturing for the exploration and appraisal phase (UKOOG, 2013b).

3.5 Consultation

A number of commentators in the US and Canada have expressed concern that public health agencies are not engaged with industry and policy makers over the regulation of shale gas extraction/exploitation (Goldstein et al, 2012; New York Health Professionals, 2011). This should not be an issue in the UK as public health bodies play an important role in both planning and permitting of industry by acting as independent consultees in both these processes. Currently, all onshore oil and gas exploration sites currently require bespoke environmental permits, although the Environment Agency is aiming to produce standard rules permits in the near future. Therefore, at present, public health professionals are consulted on bespoke environmental permit applications. Similarly, local public health professionals would be expected to play an active role during planning applications. Both processes will help ensure that public health agencies participate in, and contribute to, initiatives around the regulation of shale gas.

The general public is afforded opportunities to comment on shale gas developments. Planning authorities are required to advertise and consult on individual planning applications, while the Environment Agency also carries out public consultations for environmental permits (EA, 2010). As a matter of best practice, UKOOG's charter also sets out that communities must be engaged from the very start of the planning application process, where shale gas is being developed (DECC, 2013).

3.6 Summary

In summary, before commencing drilling operations for onshore oil and gas development the operator must have followed a number of steps, as specified by DECC (2013):

- **a** Obtained a petroleum exploration and development licence (PEDL) from DECC or petroleum licence (PL) from DETI
- **b** Secured a lease from the landowner
- **c** Submitted relevant petroleum operations notifications (PON) to DECC/DETI
- **d** Satisfied DECC/DETI that effective operational and environmental management systems are in place
- **e** Secured planning permission from the MPA/LPA/DOE
- **f** Discharged any relevant conditions placed on the planning permission by the MPA/LPA/DOE
- **g** Obtained a permit from the Coal Authority if the well will encroach on coal seams (excluding NI)

h Informed the BGS/Geological Survey of Northern Ireland (GSNI) of the intention to drill

i Completed the necessary consultation processes with all the statutory/relevant consultees

j Obtained all the necessary permits from the relevant environmental agency (EA/NRW/SEPA/NIEA)

k Notified the HSE/HSENI of the intention to drill (minimum 21 days' notice)

l Provided HSE/HSENI with details of the proposed well design that have been examined by an independent and competent well examiner (minimum 21 days' notice)

m Agreed data-reporting methods with DECC/DETI

n Agreed a method for monitoring induced seismicity and fracture growth height with DECC/DETI, where hydraulic fracturing is planned

o Received approval for an outline hydraulic fracturing programme from DECC/DETI, where hydraulic fracturing is planned

4 AIR QUALITY

4.1 Introduction

A review of the peer reviewed scientific literature and discussions with key agencies did not identify any UK data (published or unpublished) on emissions to air associated with hydraulic fracturing or shale gas extraction. There is one site that has been operating in the UK since 1996 at Elswick, Lancashire, with vertical hydraulic fracturing to release gas in sandstone formations, but no data on air emissions associated with this site appears to have been published. Similarly, no air quality data have been obtained for more recent exploratory drilling for shale gas at Preese Hall, Lancashire.

Potential impacts on air quality have been assessed by the European Commission (AEA Technology, 2012a) with much of its review focusing on data from the US. A number of studies and data suggest that shale gas extraction operations can be a source of air pollution, both primary pollutants such as oxides of nitrogen (NO_x) and particulate matter (PM) and the precursors of secondary pollutants such as ozone (O_3). Emission inventories relating to commercial shale gas extraction and related activities in Texas (Barnett and Haynesville shales), Arkansas and Pennsylvania have been considered, as have studies on air quality in Alberta, Canada, which has a large number of industrial sources including natural gas wells (Simpson et al, 2013).

4.2 Evidence on key pollutants and their sources

Published evidence from the US and other countries suggests a potentially wide variety of different sources of air pollutants from shale gas extraction and related activities. Sources can include:

a Direct emissions from engines powering the drilling and hydraulic fracturing operations and compressors used to capture and transport the gas on-site. Pollutants can include particulate matter (PM), carbon monoxide (CO), and NO_x, including nitrogen dioxide (NO_2)

- **b** Emissions from the venting of condensate and oil tanks on site. Pollutants can include a range of volatile organic compounds (VOCs)
- **c** Emissions from gas capture and flaring. Pollutants can include methane, NO_x and other gases associated with the flaring of the gas as well as PM
- **d** Fugitive emissions associated with leaks from pumps, flanges, valves, pipe connectors, etc. Pollutants can include methane and other gases

On a site-by-site basis, the current evidence suggests that emissions from individual shale gas wells are relatively small, intermittent and not unique to shale gas extraction and related activities. However, the number of wells in an area can be considerable and the cumulative impact of emissions (including fugitive emissions) might therefore be significant. Emissions of a number of air pollutants associated with shale gas extraction and related activities can lead to the formation of secondary pollutants such as O_3, which is generated by photochemical reactions involving nitrogen oxides (NO_x), volatile organic compounds (VOCs) formed in the presence of sunlight, and secondary particles. However, many pollutants associated with shale gas extraction are also produced in significant quantities from other sources, including industry and transport, and from atmospheric processes, and therefore there will be an existing background level of both primary and secondary pollution.

The air monitoring network in the Barnett Shale region of Texas is among the most extensive in the US and offers the opportunity to better understand the impact of shale gas activities on ambient air. Zielinska et al (2010) analysed air pollutants associated with shale gas extraction and related activities in the Barnett Shale region. Air quality canister sampling identified 70 individual VOCs in the vicinity of the compressor station, functioning wells and condensate tanks, and during associated transport operations on- and off-site. The most abundant non-methane VOCs were ethane, propane, butane and pentanes, which accounted for approximately 90% of the total emissions. The key source appeared to be malfunctioning condensate tanks. Emissions from these condensate tanks were localised and reported concentrations in ambient air decreased significantly downwind from the tanks. Higher molecular weight hydrocarbons were less common and mostly associated with vehicle exhaust emissions and combined natural gas and condensate tank emissions.

Further work in the Barnett Shale has been able to identify pollution signatures that may be associated with different phases of shale gas development. Rich et al (2014) collected air samples from residential areas close to shale gas wells in the Dallas/Fort Worth area between 2008 and 2010. Methane and a wide range of chemicals were detected, including benzene, xylene and toluene. Activities associated with shale gas were considered the most likely source of these pollutants; samples were collected from residential areas where there were no other obvious emission sources except traffic. The researchers undertook a principal component analysis (PCA), which is a way of identifying patterns in data. The PCA identified seven chemicals (o-xylene, ethylbenzene, 1,2,4-trimethylbenzene, m- and p-xylene, 1,3,5-trimethylbenzene, toluene and benzene), which may provide a pollution signature of emissions specific to shale gas.

Emission data from shale gas extraction and related activities in Fayetteville Shale (Arkansas) in 2008 shows that natural gas production (including shale gas) was a significant source of many common air pollutants (Department of Environmental Quality, 2011). The inventory indicated that it was not just emissions from the gas capture and hydraulic fracturing process that were identified but that emissions from engines powering compressors, drilling rigs and the hydraulic fracturing pumps were also significant. Emissions from compressor engines were the main sources of NO_x, CO, PM_{10}*, sulphur dioxide (SO_2) and carbon dioxide (CO_2).

An emission inventory has been developed for the Marcellus Shale which lies under parts of Pennsylvania, Ohio, West Virginia, New York and Maryland. This inventory, described in a paper by Roy et al (2014), delineates emissions for the major activities associated with shale gas development, including drilling, hydraulic fracturing, engines and compressors, flaring and associated traffic-related emissions. This study provided estimates of emissions for 2009 and projected emissions to 2020 using emission factors and data on the number of wells drilled and gas extracted. These estimates suggest that drilling in the Marcellus Shale could be an important source of NO_x and VOCs, with the suggestion that shale gas may contribute 12% of NO_x and VOCs in the region by 2020. Given the role of these pollutants in the formation of O_3, this could have a significant impact on O_3 levels in ambient air. The inventory also examined particulate matter ($PM_{2.5}$†) and estimates suggest that shale gas development would not make a significant contribution to regional level $PM_{2.5}$ levels. Projected estimates for 2020 have substantial uncertainties as they make assumptions about future control measures; more stringent future controls on emissions would have a marked impact on predicted emissions.

Emissions from shale gas drilling were reported as part of a hydrocarbon emissions study in the Denver-Julesburg Fossil Fuel Basin, Colorado (Pétron et al, 2012). This study involved the collection of daily air samples at the National Oceanic and Atmospheric Administration Boulder Atmospheric Observatory, which were then analysed for methane and non-methane VOCs. Other sources in the area included other oil and gas operations, a landfill site, a wastewater treatment plant and motor vehicle emissions. Oil and gas activities including shale gas extraction and related activities were strongly associated with alkane and benzene levels in the atmosphere. Key sources of emissions appeared to be flashing from condensate tanks, involving release of gases dissolved in the liquid condensate due to decreasing atmospheric pressure, and venting of oil or gas wells.

These emission inventories also show that the composition of shale gas will vary due to differences in shale beds. There are two types of shale gas: wet gas and dry gas. Both types are predominantly methane, but wet gas also contains hydrocarbons such as ethane and butane which are termed natural gas liquids. These hydrocarbons can be separated out from the methane and processed for sale. As gas extracted from wet shale beds contains more natural gas liquids, there is an associated greater potential to emit more VOCs during capture and further processing. The storage of hydrocarbons in condensate tanks can be a source of VOC emissions. Emissions of VOCs can vary considerably; gas collected from Fayetteville Shale differed markedly from that reported for Barnett Shale. The type of gas can also vary within the shale beds: for example, most of the Marcellus Shale is dry but wet gas is extracted from the Marcellus Shale in southwest Pennsylvania (Roy et al, 2014). Such variability in gas type and resulting emissions emphasises the need for assessment of emissions on a case-by-case basis.

As stated above, VOCs and NO_x are important precursors for O_3 formation and the potential impact of shale gas extraction and related activities on regional O_3 levels has been investigated in the Haynesville Shale which covers Northeast Texas and Northwest Louisiana

* PM_{10} represents the mass concentration of all particles of generally less than 10 μm aerodynamic diameter. This fraction can pass the thorax and enter the conducting airways.

† $PM_{2.5}$ is the mass concentration of particles of generally less than 2.5 μm aerodynamic diameter. This fraction can penetrate deep into the lungs.

(Kemball-Cook et al, 2010, 2012). Based on well production data from state regulatory agencies and experience from other developments (especially the nearby Barnett Shale), projections of future Haynesville Shale natural gas production were derived for 2009–2020 for three scenarios corresponding to limited, moderate and aggressive development. These estimates indicated that projected emissions of O_3 precursors, in this case NO_x, from the exploration and development phase could have a sufficiently large impact on O_3 levels in Northeast Texas and Northwest Louisiana to result in these areas failing to meet the relevant health standard/guidelines for O_3. It was also suggested that emissions from the Haynesville Shale could affect other regions due to long-distance O_3 transport.

The potential impact of shale gas emissions on O_3 levels has also been reported in other states in the US. In a study in Colorado, VOC emissions from shale gas operations were found to be a significant source of O_3 precursors (Gilman et al, 2013). In this study, Gilman et al were able to identify a specific VOC signature associated with shale gas when compared with other sources such as motor vehicles. Light alkanes were a key component of this source signature and possibly indicative of certain shale gas activities. This study further demonstrates that regions with a high density of shale gas wells can have a potentially significant impact on O_3 levels through emissions of VOC precursors.

In a study in Texas, emissions of NO_x and formaldehyde from flares and compressor engines in the Barnett Shale gas field were found to increase levels of O_3 in the area (Olaguer, 2012). Using a dispersion model, emissions of NO_x from flares and engines were predicted to significantly contribute to peak one-hour concentrations in close proximity to the drilling wells. It was suggested that such emissions, when combined with background levels of O_3, could result in non-attainment of US O_3 standards and, as a result, the study recommended that further regulation was required to control emission sources associated with shale gas.

Colborn and colleagues (Colborn et al, 2011, 2012) examined the potential impact of shale gas extraction and related activities on local air quality in the US. In 2011 they noted the importance of emissions of VOCs and exhaust emissions from on-site generators and concluded that air quality monitoring for individual VOCs and O_3 must be a requirement of shale gas regulation. They also stressed the need for monitoring to start before drilling to establish baseline levels against which impacts can be measured. Colborn et al (2012) collected weekly air samples in western Colorado for a one-year period from a fixed air monitoring station near to a well pad on which 16 wells were drilled and fractured. A range of air pollutants was detected, including a range of VOCs, carbonyls such as formaldehyde and a number of polyaromatic hydrocarbons (PAHs). However, many of these pollutants are ubiquitous in the environment and other sources such as road traffic and other industry would also have been important contributors to the ambient background. The study did show clear variations in the type of pollutants reported, which may have been related to different activities on the well pad as well as variations due to seasonal factors and prevailing wind conditions. For example, concentrations of the non-methane hydrocarbons, typically light alkanes and alkenes, were highest during the initial drilling phase which precedes the actual fracturing process.

A review for the European Commission examined potential emissions to air during the various stages of shale gas development and production. The review concluded that the type and source of emissions varied with the different phases of well development (AEA Technology, 2012a). The importance of diesel emissions from drilling equipment and associated traffic was highlighted. The evidence indicated that while impacts from individual sites were likely to be minor, the cumulative impact from multiple sites could potentially be more significant, especially in terms of impacts on regional air quality such as elevated levels of O_3. As a result, this preliminary risk assessment for the European Commission concluded that the potential risks to human health and the environment from releases to air across all phases of development was high.

The hydraulic fracturing of wells can often involve large amounts of sand that act as a proppant to hold the fractures open and so facilitate the flowback of gas. Occupational exposure to silica is a well-established hazard in many industries which use large amounts of sand, such as mining, foundry work and construction. Esswein et al (2013) reported that similar occupational hazards exist within the shale gas industry and recommended controls to minimise exposure, such as measures to reduce dust generation, the use of different proppants and appropriate personal protective equipment. While the study does not consider potential impacts of silica dust off-site, measures to protect the workforce should also help ensure local communities are not exposed to silica dust.

In addition to pollutants associated with the drilling, fracturing and related infrastructure (such as compressors and diesel engines), shale gas itself is predominantly methane, which is a flammable gas and explosive in air at concentrations between 5 and 15% by volume. While methane can present a risk to health in confined spaces where high concentrations build up and displace oxygen from the air, emissions of methane from shale gas extraction and related activities are not expected to be an immediate threat to public health. Evidence from the US suggests that methane releases to air from deep shale measures tend to be via failures in well infrastructure and inefficient gas capture rather than directly from gas migrating through overlying rock (US EPA, 2013). In the UK, operators will be subject to the conditions laid out in environmental permits to minimise fugitive emissions of methane and appropriate management of waste gas (EA, 2013a).

4.3 Regulation and monitoring

Regulations covering shale gas extraction and related activities apply in some states of the US, including monitoring requirements for classical air pollutants such as: CO; lead (Pb); nitrogen dioxide (NO_2); particulate matter (typically $PM_{2.5}$); SO_2; and O_3 precursors. In addition, there are monitoring requirements for organic air pollutants such as a range of VOCs including BTEX (benzene, toluene, ethylbenzene and xylene), formaldehyde, hexane and 2,2,4-trimethylpentane. Methane emissions are also often monitored as part of climate change assessments.

In April 2012 the US EPA announced new and updated air pollution regulations for natural gas facilities including shale gas extraction and related activities. These regulations cover both the facility and other elements of oil and natural gas development, including emissions from on-site equipment such as processing plants, storage tanks and compressors as well as from the gas wells themselves. The key tool in these regulations is the use of pollution abatement equipment to control and reduce emissions from the gases, liquids and other substances that flow from the well (Weinhold, 2012). The aim is to ensure efficient capture of the gas produced and thereby reduce emissions. Completing a well installation with such equipment is called ‘green completion’. Since much of the captured gas includes products with a market value, such as propane and butane, there is also a financial incentive. Flaring of gas is not encouraged as this can create combustion pollutants such as CO, NO_x, PM and CO_2.

Reductions in emissions from on-site equipment and additional reporting requirements are included within the regulations. The US EPA estimates that the green completion process and other associated changes will cut VOC emissions by 95%.

In addition to these new regulations, a number of US states have started to develop emission inventories and region-wide monitoring programmes to better quantify the extent and significance of emissions from unconventional gas extraction. Pennsylvania is currently collating an emission inventory which requires reporting for a range of air pollutants including CO, NO_x, PM_{10}, $PM_{2.5}$, SO_2 and VOCs. Additional reporting is required for benzene, ethylbenzene, formaldehyde, *N*-hexane, toluene and 2,2,4-trimethylpentane. Other states have already published their inventories, including Arkansas and Texas. In New Brunswick, Canada, the Chief Medical Officer recommended that the province establish monitoring networks for ambient air in local areas expected to have shale gas production (Office of the Chief Medical Officer of Health, 2012) . It was recommended that these monitoring networks should be able to detect both local and regional impacts of emissions and provide baseline monitoring as well as monitoring during the lifetime of the development and post-production.

The emerging evidence suggests that while emissions (both direct and fugitive) from single wells are relatively small and possibly insignificant, cumulative emissions from many shale gas extraction wells can be significant. Litovitz et al (2013) estimated that in counties in Pennsylvania with a high density of wells, NO_x emissions could range from 20–40 times that allowed for a single ‘major’ emission source. The potential cumulative impact of many wells presents a challenge to regulators, particularly as emissions associated with individual wells may be below levels requiring specific regulation. Litovitz et al estimated a small contribution of VOCs, NO_x and $PM_{2.5}$ from transportation sources relative to direct emissions from drilling and the use of compressors.

Experience from the US and other countries demonstrates the need to collect a comprehensive dataset on emissions from shale gas production activities and to consider the impact of cumulative emissions in areas with a high density of wells. This should include the development of emission inventories and regular monitoring of ambient air quality around shale gas extraction sites and their associated activities. Without such data, it would not be possible to undertake a reliable analysis of the impact of emissions on human health. Moore et al (2014) reviewed the impact of shale gas activities in the US in terms of gaseous releases and concluded that there are critical gaps in emission data for the individual phases of shale gas development. They recommended that air quality measurements need to be made before and during operations to better understand the impact on air quality and the effectiveness of emission control strategies. Such measurements need to include a full chemical analysis to aid source apportionment studies and understand the potential impact on air quality and health of all phases of shale gas development.

The variety of emission sources also emphasises the need for appropriate regulatory control in the UK to ensure that all emissions associated with shale gas exploration and exploitation, both direct and fugitive, are assessed and controlled. This should include the assessment of emissions as part of local air quality management strategies. However, it is important to understand that background levels of air pollution vary from place to place in the UK. In some areas, specific sources will dominate, such as near roads from pollutants emitted by vehicles, while, in other areas, these sources will be less important and levels will be dominated by regional, national and even international sources. Many of the pollutants associated with shale gas activities are not unique to shale gas extraction. Therefore emissions from shale gas operations will need to be assessed in relation to existing background levels of ambient air pollution and their variation.

In the UK, many industries and processes (and not just shale gas) are regulated for emissions to the environment, including air. The aim of such regulations is to reduce emissions to the atmosphere and help maintain and improve air quality. As such, industry is set emissions limits that have regard to relevant air quality standards and must comply with regulations that are protective of health.

4.4 Human health risk assessment

The published literature on the risk to human health from shale gas extraction is limited but increasing. Colborn et al (2011) reviewed the toxicity for over 600 chemicals used in the hydraulic fracturing process and identified a number of potential health outcomes that could result from exposure. However, there have been very few epidemiological studies or health risk assessments published in the peer reviewed literature.

The Colorado School of Public Health research group has published two risk assessments looking at possible associations between health status and exposure to air pollutants from shale gas activities. McKenzie et al (2012) used a risk assessment methodology which considers cancer and non-cancer endpoints separately to assess the potential health impact of air emissions from shale gas extraction and related activities. It should be noted that the risk assessment methodology used in this study is not recommended for use in the UK. McKenzie et al (2014) examined a possible link between air pollution and adverse birth outcomes, including congenital malformations. Both papers are discussed in some detail below.

Cumulative non-cancer hazards were estimated by McKenzie et al (2012) using a hazard index (HI) approach, where the ratio of estimated exposure is compared with a health based guideline value (in this case reference concentrations, RfCs) to produce hazard quotients (HQ) for each chemical, which are summed to produce an HI. If the resultant HI is greater than one, there is an indication of the potential for health concern. The HI assumes cumulative (ie additive) effects of chemicals; it can be calculated assuming additivity across all chemicals and effects, or an HI for a specific endpoint can be estimated by including only substances which exert this effect. Chosen non-cancer endpoints included neurological, respiratory, haematological and developmental effects.

Chronic HIs were calculated for a full 30-year project duration, and subchronic HIs using subchronic RfCs, where available, for a 20-month exposure period during the well development phase. In respect of cancer, lifetime risks were estimated by multiplying the estimated exposure, over a 30-year project lifespan, by the inhalation risk derived by the US EPA or Californian EPA for each chemical and these results were summed to estimate the cumulative cancer risk.

The risk estimates from the HI approach identified well development and completion (about 20-months' exposure to hydrocarbons) as posing the highest risk to the nearby population, resident within half a mile (an HI of 5 based on the 95% upper confidence limit (UCL) of the mean concentration, and an HI of 0.4 based on the median exposure). The main health endpoint of concern was neurological effects with trimethylbenzenes the main causative agents, but haematological, respiratory and developmental effects all contributed to the combined HI. Estimated cancer risks and chronic non-cancer hazard indices were greatest for residents living within half a mile of the nearest well pads, with a 1 in 10^5 cancer risk and an HI of 1 (based on the 95% UCL of the mean concentrations), compared to a 6 in 10^6 cancer risk and an HI of 0.4 in those living over half a mile from the nearest pads. Benzene and ethylbenzene were the main contributors to cancer risks, but overall the concentrations of both chemicals were similar to those found more generally in urban areas in the US. The key finding was that the calculated potential for risks for sub-chronic non-cancer endpoints (20-months' exposure) were elevated for those residents living within half a mile of the gas wells during well completion.

In the UK, risk assessments are usually based on the most sensitive health endpoint, rather than undertaking evaluations for cancer and non-cancer effects separately. Also, the approach used for cancer risk assessment in the US is not recommended for use in the UK by the UK advisory Committee on Carcinogenicity of Chemicals in Food, Consumer Products and the Environment (COC) if the risk values used are derived from animal data (COC, 2012). Nevertheless, McKenzie et al (2012) indicated that emissions to air from activities associated with the drilling and development of gas wells can be significant locally and, like other sources of air pollution, may present a potential risk to health. The paper suggests that the potential risks from sub-chronic exposure are of most concern, especially among residents closest to the well pad. The key exposure appears to be from chemicals emitted during well development and completion activities. It is also clear that emissions to air come from a variety of sources associated with the drilling and operation of a well pad and are not simply associated with the extraction of gas from the well itself. It is unlikely that the results presented by McKenzie et al (2012) are directly applicable to other extraction sites either in the US or in other countries since local factors such as type and duration of drilling, local meteorology and topography will vary between well sites. The researchers are clear that this was a preliminary study and the results showed a need for further research. Prevention strategies to minimise exposures during well completion activities are recommended.

The paper has a number of limitations and uncertainties, many of which are acknowledged by the authors. These include:

- **a** Small sample size and the limited amount of data on emissions around well completion sites
- **b** Further work is needed to profile emissions during the stages of gas well development
- **c** Non-methane pollutant emissions appear to vary substantially by field type, number of well heads, completion process and types of controls in place. This makes application of the results to other shale gas extraction sites difficult
- **d** A limited number of volatile organic compounds was explored. Other pollutants such as aldehydes, diesel exhaust, O_3 and PM, were not considered
- **e** The existing background level of pollution needs further assessment to enable pollution caused by shale gas extraction and related activities to be reliably assessed
- **f** The impact of local meteorology and topography means that the results are not easily applicable to other areas and other extraction sites

More recently, the same research group has examined a possible link between maternal exposure to air pollutants associated with shale gas extraction activities and birth outcomes such as congenital heart defects, neural tube defects and low birth weight (McKenzie et al, 2014). This large cohort study examined 124,842 births between 1996 and 2009 in rural

Colorado. Exposure was assessed using an inverse distance weighted approach based on maternal residence at birth, taking account of all existing natural gas wells within a 10-mile radius to create tertiles for high, medium and low exposure. Further sensitivity analysis was undertaken for births from 2000–2009, which was the period of rapid expansion of shale gas development including hydraulic fracturing and directional drilling. The birth outcomes considered were oral clefts, neural tube defects, congenital heart defects, preterm birth, term low birth weight, and term birth weight (as a continual measure). Data from birth registries, hospital records and screening programmes for oral cleft, neural tube defects and congenital heart defects was used to identify cases.

McKenzie et al (2014) reported a positive association between exposure (as measured by density and proximity of natural gas wells) and prevalence of congenital heart defects. The association with neural tube defects was considerably weaker. The reported odds ratios have wide confidence intervals which weaken the reported association and chance findings cannot be excluded, given the number of analyses carried out. The exposure assessments relied upon an indirect approach rather than direct measurements of exposure. Furthermore, the study was unable to differentiate between the phases of well development, which could be important in terms of the type of and amount of pollutants emitted. Maternal education, age, smoking status and alcohol consumption were considered as potential confounding factors, but it is not clear that confounding was adequately addressed for socioeconomic status or previous experience of birth defects. Overall, the study suggests a possible link between maternal exposure to air pollutants which may arise from shale gas extraction activities and a range of birth defects, particularly congenital heart defects, although the authors acknowledge that further research is needed to examine whether a link with shale gas drilling was causal. The obvious limitations in terms of exposure assessment highlight the need for such health studies to have access to robust assessments of exposure both before and after development of a site for gas exploration and extraction.

In Pennsylvania, an epidemiological study has examined the incidence of childhood cancer before and after drilling for shale gas (Fryzek et al, 2013). This study examined all cancers in children below the age of 20 years at a county level, the smallest area for which cancer and population data was available. Data was analysed for the period 1990–2009 and the observed number of cancers was compared with that expected for two periods of time: from 1990 to the year before the first well was drilled and from the year the first well was drilled to 2009. During this 20-year period, more than 29,000 wells were drilled, with the number steadily increasing between 2003 and 2008. The study results suggest that the number of childhood cancers observed was very similar to the number expected and there did not appear to be any statistically significant trends in cancer incidence with well density. Slightly more central nervous system tumours were reported in areas after drilling, although this result was seen only in counties with the fewest number of wells and no relationship was apparent with the number of wells drilled. There was no evidence of an increase in childhood cancer following drilling activities. The study had a number of limitations. Data was only available at a county-wide level and no direct measurements were made of exposure. The period of data analysis after drilling was generally too short for an adequate assessment of cancer risks, given latency in cancer development. Such concerns were raised by Goldstein and Malone (2013).

The Barnett Shale is a large shale gas field in North Texas that has been subjected to a considerable amount of environmental and, more recently, health monitoring. The potential health impact of VOCs in ambient air in this region have been estimated using health based air standards and through risk assessment (Bunch et al, 2014). In this study, data on VOCs measured by seven fixed monitors at six sites in the Dallas/Fort Worth region was analysed up to 2011. Maximum hourly, 24-hour and annual average concentrations were calculated and compared with appropriate federal and state health based standards (termed health based air comparison values or HBACV) for both acute and chronic health effects. None of the measured values exceeded the acute HBACV, suggesting that ambient concentrations of VOCs were unlikely to present an acute risk to health. In terms of a chronic risk to health, one VOC, 1,2-dibromoethane, exceeded the chronic HBACV at two of the monitoring sites in 2011. In both cases, the annual average was more than double the chronic HBACV. No other exceedances of this or any other VOC were recorded at this or any other monitoring site through the period of investigation. The study investigators felt that the source of this VOC might not be due to shale gas extraction activity as this chemical is widely used in aviation fuel and in off-road automobile racing. A large number of non-detect values within the 1,2-dibromoethane dataset meant that the annual average was calculated entirely from the sample limit of detection rather than from actual measurements, which might have influenced the annual average.

As part of the study, monitored VOCs were also assessed in relation to chronic and non-chronic effects using deterministic and probabilistic risk assessments. In the majority of cases, estimated cancer and non-cancer risks were within acceptable risk ranges, although at one site the cancer risk was estimated to be above acceptable ranges. Again, 1,2-dibromoethane was thought to have driven up the estimated cancer risks. The authors concluded that the dataset did not suggest that the local community was being exposed to harmful levels of VOCs from shale gas extraction activities or other industrial activities in the Barnett Shale region. Although the dataset used is very large and comprehensive, uncertainties remain in extrapolating monitoring data from fixed monitoring sites to estimate wider community exposure.

The town of Dish is located over the Barnett Shale and local residents have reported concerns over pollution associated with the gas wells and associated infrastructure. In 2009, the Texas Department of State Health Services undertook a small exposure study to investigate whether local residents had raised levels of chemicals in their blood and urine that could be associated with shale gas activities (Texas Department of State Health Services, 2010). Blood and urine samples were collected from 28 residents living in and near the town. Samples were analysed for a total of 33 VOCs, including benzene, and blood results were compared with reference data for the general population collected by the National Health and Nutrition Examination Survey (NHANES). In addition to providing blood and urine samples, residents were interviewed and asked to remain in their homes for four hours before the collection of biological samples to provide a representation of residential exposure. There were no significant differences in the concentration or pattern of VOCs in Dish residents compared with the national dataset. The types of VOCs and levels were consistent with exposure to sources such as smoking and the use of consumer products such as household cleaners and chemicals associated with water disinfection products. Benzene and styrene were recorded at levels above the national reference levels in four people but smoking was considered the likely source of these levels. Similarly, levels of VOCs in urine were also unremarkable and consistent with reported data for the general population. During the study, residents reported a range of health symptoms such as headache, respiratory problems and eye irritation, but the cause of these symptoms could not be determined and it was concluded that there may a number of causes.

Health concerns have been examined in communities living on the Marcellus Shale, Pennsylvania (Ferrar et al, 2013a). In this study 33 people living close to shale gas wells were interviewed on two separate occasions to identify their health concerns relative to shale gas ('stressors'). Participants reported 59 separate health impacts and 13 stressors, including impacts such as rashes, muscle and joint aches, digestive problems, central nervous system effects, respiratory and cardiac symptoms, and psychological symptoms such as sleep loss and, most frequently, stress. Over the duration of the study, the perceived health impacts increased, although stress-related symptoms remained relatively constant. The small sample size of the population was a major limiting factor in this study as was self-reporting of symptoms and impacts. Many of the symptoms reported were non-specific with multiple possible causes. The authors suggested the need for robust public health monitoring among communities living in areas with a high density of shale gas wells as well as better engagement of public health professionals in understanding the potential impacts of this and other industries.

Self-reported health surveys have also been used to investigate community health in Pennsylvania (Steinzor et al, 2013). In this case, a self-reporting survey was sent to 108 individuals (in 55 households) in 14 counties in Pennsylvania between August 2011 and July 2012. Participants were asked to complete a checklist of symptoms. Questions on occupational status, related chemical exposure history such as smoking, underlying health status, type and frequency of chemical odours and distance from shale gas wells were also asked. Environmental monitoring of outdoor ambient air at the property (and drinking water) was undertaken on a subset of the study population (70 homes). The study reported a high number of symptoms in the study population, with fatigue, eye, nose and throat irritation, tiredness and headache particularly prevalent. Many of the symptoms were reported irrespective of proximity to shale gas activities, although some symptoms, such as throat irritation, were most commonly reported by people living nearest to a well. Ambient air was collected over a 24-hour period and analysed for a ranges of VOCs. The number and type of VOCs varied considerably and there was little discernible pattern with geographical location and proximity to a well. The study suffers from a number of limitations. The symptoms are self-reported and there does not appear to be any evidence of reported symptoms being clinically confirmed. Many of the symptoms reported are non-specific and will have a multitude of causes which have not been considered. Furthermore the study lacks a control group of unexposed people. The exposure assessment for ambient air is based on a very short duration (24 hours) and this, together with a lack of any consideration of topography, prevailing wind direction, other emissions sources in the area or evidence of any recorded activities at the wells, makes it difficult to infer any link with shale gas extraction activities. The researchers acknowledge that the study is unable to show a direct cause and effect relationship.

4.5 Summary

There are a large number of different sources of gaseous emissions during shale gas extraction and associated activities, including those directly relating to gas capturing and flaring and those from infrastructure sources such as the use of diesel engines, storage tanks and vehicles. Emissions will vary between sites due to differences in the underlying geology and the maturity of the shale. Emissions from specific sites will vary temporally, with different pollutants emitted during different phases of well development and operations, and will vary spatially because operations may be across many individual wells, each at different stages of development. Local topography and meteorological conditions will also add to the difficulties in accurately assessing dispersion and potential exposure.

Published studies in the US have begun to assess the potential impact of shale gas extraction and related activities on local air quality through emissions inventories, although the level and type of emissions during all stages of shale gas development and production are not fully characterised. The available evidence indicates that a large number of VOCs may be emitted, depending on the source, operational practices at the extraction site and level of VOCs in the shale gas itself, and that these emissions can impact on local air quality.

Shale gas extraction and related activities can be major sources of classical air pollutants such as PM, NO_x, SO_2 and benzene and also of O_3 formed from primary emissions. The available evidence suggests that while emissions from individual well pads are low and unlikely to have an impact on local air quality, the cumulative impact of a number of well pads might be significant locally and regionally, especially in areas with a high density of wells. In the US, shale gas fields are associated with ground-level O_3 pollution due to the emission of O_3 precursors such as NO_x and VOCs. Multiple sites can also be a significant source of particulate matter, especially diesel particulates from the compressors, engines and traffic associated with production.

It is clear from experience in the US that emissions vary widely depending on the phase of development, operational practices, the geology, local topography and meteorology, and the types of activities and equipment on-site. Such variability makes direct application to the UK situation impossible, but shows that control of emissions from shale gas extraction and related activities will be of central importance. Comprehensive air monitoring and associated assessments of health risks will be required in the UK to inform regulation of each phase of the operation. Such assessments should also consider the cumulative impact of multiple wells. It will be important to ensure that environmental monitoring is undertaken in advance of, as well as during, operations.

4.6 Gaps in knowledge and recommendations for further work

Evidence suggests that the composition of shale gas will vary according to geology and, as a result, each shale bed will need a detailed risk assessment. Comprehensive air quality monitoring is needed to enable exposure assessment and should be a critical part of any risk assessment process. The air quality monitoring will allow the development of detailed emission inventories which need to consider the stage and phase of well development as evidence indicates that this will influence the emission profile.

The available evidence suggests that the impact of individual wells on air quality is likely to be low and particular emphasis should be on assessing the cumulative impacts of emissions on air quality from multiple drilling sites. Air monitoring should reflect this concern and consider not only local air quality impacts but also the potential for local and regional air quality effects due to pollutants such as ground-level O_3, PM and NO_x/NO_2. Any future regulatory regime should clarify responsibilities in terms of local air quality assessments. It is recommended that public health professionals work with regulators to ensure air monitoring around such sites will provide the information necessary to assess the potential for any impact on public health.

UK risk assessment will ideally apply an agreed methodology for assessing the health effects of exposures to mixtures of VOCs and other pollutants from the various phases of shale gas extraction and related activities. This should include assessment of all exposures over the lifetime of the well pad corresponding to particular stages of the process, eg drilling, fracturing, extraction and production.

5 RADON

5.1 Introduction

Some radionuclides, including members of the uranium and thorium radioactive decay chains, are naturally present in soils and rocks. Certain soils and rocks, including granites, limestones and shales, are associated with relatively high levels of these radionuclides and members of their radioactive decay chains. The concentration of uranium-238 in soil varies. This activity concentration is generally measured as the number of radioactive decays per second (in becquerels, Bq) in unit mass of soil. Within the UK, it ranges from 2 to 330 Bq kg^{-1} (UNSCEAR, 2010).

Radon-222, a noble gas, is a member of the uranium-238 radioactive decay chain. It is released to air from most of the land surface of the Earth. Radium-226, with a radioactive half-life of 1,600 years, is the immediate precursor to radon-222 in the decay chain. Uranium-238, radium-226 and radon-222 all decay by the emission of alpha particles. Most of the radiation exposure from radon-222 arises from its short-lived radioactive progeny, which decay by a mixture of alpha and beta particle emission. The release of radon from rocks and soils is determined largely by the types of minerals in which uranium occurs. Since radon is a gas, it has much greater mobility than other radionuclides in the uranium radioactive decay chain, which are fixed in the solid matrix in rocks and soils. Radon can more easily leave the rocks and soils by escaping into fractures and openings in rocks and into the pore spaces between grains of soil. If radon is able to move easily in the pore space, it can travel some distance before it undergoes radioactive decay (radioactive half-life of 3.8 days). Radon migration to the surface is controlled by the transmission characteristics of rocks and soils and the nature of carrier fluids, including groundwater.

Where radon escapes to open ground, the activity concentration of radon in air is generally low, typically a few Bq m^{-3} (Wrixon et al, 1988). Where radon is drawn into buildings, due to indoor pressure differential and the containment caused by the building, concentrations of radon can be significantly higher, in some cases many thousands of Bq m^{-3}. In order to control exposure to radon, measured indoor air concentrations are compared against action levels. Where an action level is exceeded, remediation is encouraged.

Exposure to natural sources of radiation contributes approximately 84% of the average annual dose of radiation to a member of the UK population (Watson et al, 2005). This exposure comes from both intakes of radionuclides from air and within food, as well as from external exposure to radionuclides present in the ground and from space. Exposure to indoor radon is generally the most significant source of radiation exposure to the UK population, contributing an average of around half of the total dose (Watson et al, 2005).

A review of the literature, and discussions with key agencies, did not identify any UK-specific data on radon associated with shale gas extraction and related activities. Some measurements of radon relating to shale gas extraction activities have been reported in the US. These are discussed in Section 5.3.

Section 6 of this report considers naturally occurring radioactive materials (NORM). A number of reports (eg Walter et al, 2012) have looked specifically at radon emissions from NORM scenarios. It would be appropriate to include assessment of radon releases in assessments of NORM, although releases of radon to open air are likely to lead to minimal public radiation exposure.

5.2 Radon released to air from the Earth's surface

Radon is released to air from near-surface soil and rock structures through the local natural network of voids, cracks, etc. In most situations, this release is from material in the upper few metres of the Earth's surface. Small-scale disturbances to this network might lead to short-term changes in the rate of release but would not lead to significant or sustained changes in the long-term release rate of radon to atmosphere. The substantial depth at which hydraulic fracturing is expected to take place, means that it is difficult to envisage how it might cause the physical changes that would be necessary to result in a significant short- or long-term change in the release of radon from the Earth's surface.

Boreholes for shale gas exploration might pass through rock layers that have naturally elevated radon concentrations. Provided the integrity of the impervious casings of these well bores is maintained, radon is unlikely to intrude into the well bore from the surrounding rock. Any radon that does enter the borehole through this route would be carried with returning fluid and be minimal in relation to, and indistinguishable from, radon that is expected to be present in the returning fluids, discussed in Section 5.5.

5.3 Radon in natural gas

Radon is present in natural gas such as shale gas. Levels vary because each well lies on different geology and has different depth and hence transit time to reach the Earth's surface. Before natural gas reaches consumers, it is generally blended and may spend time in storage or in transit from the originating well. Typical levels of radon in natural gas have been reviewed (Dixon, 2001). For typical domestic rates of gas usage with an average UK radon level of about 200 Bq m^{-3}, the estimated individual annual dose from the use of natural gas for UK residents is estimated at 4 μSv (microsieverts), which is extremely small.

The Marcellus Shale deposit in the US has been the subject of many studies. Johnson (1973) gives an average radon level in US natural gas production of 1,370 Bq m^{-3} (37 pCi l^{-1})*. A model employed by Resnikoff (2012) showed that radon levels in shale gas at the wellhead can reach 1,365–95,300 Bq m^{-3} (36.9–2,576 pCi l^{-1}). The study estimated that, depending on the gas treatment, processing as well as transport length, the radon concentrations in the shale or natural gas delivered to customers may range up to 72,000 Bq m^{-3}, resulting in indoor radon concentrations of the order of 20 Bq m^{-3}, similar to the average level of radon in indoor

* Some US reports use the unit of curie (Ci), where 1 Ci = 3.7 10^{10} Bq.

air of UK homes. These figures are based on estimated wellhead radon concentrations which are, in turn, derived from models of emanation from radium concentrations. The models do not appear to reflect any dilution of the shale-derived natural gas with natural gas from other sources and assume continuous exposure at the peak rate. Resnikoff also states that conventional wellhead concentrations were lower during a survey of the US in 1973 than estimates made in his report for wellhead concentrations associated with hydraulic fracturing.

The US Geological Service (USGS) (Rowan and Kraemer, 2012) reported measurements of radon-222 between the wellhead and gas-water separator stages of 11 hydraulic fracturing wells in the US, including some at Marcellus Shale sites. The observed values range from 37 to 2,923 Bq m^{-3}.

If the natural gas delivery point were to be close to the extraction point with a short transit time, radon present in the natural gas would have little time to decay. No UK data is yet available on radon concentrations in shale gas at the wellhead. The UK has an extensive national gas transmission system (National Grid, 2012).

There is, therefore, the potential for radon gas to be present in natural gas extracted from UK shale, as is the case with existing natural gas supplies. The radon concentration in natural gas delivered to consumers would depend on the original radon gas concentration modified by transit times, storage, dilution (with other natural gas) and the effects of any processing or blending of the natural gas. Using the existing UK model (Dixon, 2001), it is estimated that natural gas containing radon at the upper end of the range (2,923 Bq m^{-3}) reported by the USGS would give individual exposures of the order of 60 μSv y^{-1}. This is small compared with the average annual UK radon exposure of around 1,300 μSv.

Unwanted flammable gases arising from natural gas wells are sometimes flared off. Radon may be present in such gas flows. In these circumstances, any radon released would be rapidly dispersed in the atmosphere and would be very unlikely to lead to any significant public radiation exposure. Doses from this potential pathway could be assessed using information about the radon concentration in the gas, flaring practices and local atmospheric dispersion.

5.4 Radon in water

Radon and radium are relatively soluble in water and, although there is a risk associated with ingestion, most of the radiation dose associated with radon in water supplies comes from radon in air in locations where degassing occurs, such as when water is drawn from taps, etc. The highest radon concentrations tend to be found in groundwater which has been in contact with crystalline rocks but radon levels in water do vary between wells on the same geology. Surveys carried out in the UK have found some private water supplies have radon activity concentrations approaching 1,000 Bq l^{-1} (BGS and DETR, 2000), far higher than those found in public water supplies. Where high radon concentrations are found in private water supplies, reduction measures are advised. In these cases, radon that degases from the water supply often makes a significant contribution to overall exposure by adding to the total indoor airborne radon concentrations.

If hydraulic fracturing were to create new vertical fractures, or extensions to existing fractures, these might provide a pathway for contaminants from the shale layer into overlying strata. Models have indicated that normal advection times from depth to near-surface aquifers can be decreased by fracturing. Current evidence (RS and RAE, 2012) suggests that most fractures only extend a few hundred metres upwards with the chance of a fracture extending more than 600 m being exceptionally low. Radioactive decay and dilution in groundwater would both further reduce the concentration of any radon transported along such pathways. Reports from the US have indicated that radon in water from wells close to hydraulic fracturing activity is greater than elsewhere (Otton, 1992). However, the source of the elevated levels has not been clearly identified and there is natural variation in radon levels in water drawn from different sources. Myers (2012) examined the issue of transport of contaminants from deep shale beds after hydraulic fracturing and concluded that advective transport occurs on timescales very much longer than the radioactive half-life of radon. Any radon released would therefore decay before it reaches any groundwater supply via advection.

Since the expectation in the UK is that most hydraulic fracturing will occur at a considerable depth (typically more than 1,000 m below the surface) and considering the short radioactive half-life of radon relative to groundwater transit times, the impact of any radon released into groundwater would be minimal. Were shale gas extraction activities to be carried out at shallower depths, a site-specific risk assessment would be recommended.

5.5 Radon in flowback water

Radon can be present in flowback water due to its solubility. The amount of radon will also depend on the amount of its parent, radium-226. The average radon content in soil gas, measured in the US, is about 7,400–74,000 Bq m^{-3} (200–2,000 pCi l^{-1}) and may exceed 37,000,000 Bq m^{-3} (100,000 pCi l^{-1}) (Otton, 1992; Gundersen, 1993). No measurements were found specifically for radon in flowback water from shale gas operations. In the US, reported gross alpha concentrations within hydraulic fracturing flowback water were in the range 0.8–700 Bq l^{-1} (New York State Department of Environmental Conservation, 2011). Samples of flowback water from the Preese Hall exploratory site in UK showed gross alpha concentrations in the range 10–200 Bq l^{-1} (EA, 2012a). Both reports identify the presence of radium-226, the radioactive precursor of radon (see Section 6). It is likely that radon will be present in flowback water.

Radon degassing from the flowback water will be facilitated by the turbulence and high temperature of the fluid. This may lead to elevated radon levels in the proximity of the wellhead, but further studies would be required to measure the radon released during the extraction process. Since this is likely to lead to only very localised increases in airborne concentrations of radon, it is only likely to be of potential relevance to on-site occupational exposures.

Burkhart et al (2013) describes short-term field measurements made in close vicinity to a shale gas site in Colorado, US. Outdoor radon concentrations were observed in the range up to 165 Bq m^{-3}. The authors note that this is significantly above the normal outdoor levels in the US. The radon measured at this site may include contributions from multiple pathways, including shale gas or flowback water. These measurements lend weight to the expectation that some radon will be released to air from operational shale gas sites. It is expected that outdoor radon concentrations in air at further distances would be greatly diluted relative to concentrations at or adjacent to the operating site.

5.6 Summary

It is considered unlikely that shale gas extraction and related activities would lead to any significant increase in public exposure from outdoor radon levels or indoor levels in nearby homes.

In common with other sources of natural gas, there may be a potential for radiation exposure from radon in natural gas obtained from shale gas extraction but at very low levels.

The depth of shale gas extraction zones is much greater than the depth from which private water supplies are extracted from the ground. It is unlikely that radon released from shale gas zones would reach water supplies originating from the ground. Were shale gas extraction activities to be carried out at shallower depths, a site-specific risk assessment would be recommended.

Radon may be present in flowback water used in shale gas fracturing and may be released to atmosphere. Radon released in this manner is not likely to lead to significant public radiation exposure.

5.7 Gaps in knowledge and recommendations for further work

It is considered very unlikely that shale gas activities would have any significant effect on radon levels in homes. Radon levels vary between homes and higher-than-average levels occur even away from radon-prone areas. Thus, it may be that in areas where shale gas extraction takes place, some householders may choose to monitor for radon and may attribute any elevated levels to local shale gas extraction. It would be useful to have an evidence base to refer to in the event of such inquiries.

Radon is present in low concentrations in conventionally extracted natural gas and has been assessed for its radiological significance. Shale gas extraction presents a further potential source of radon in natural gas, but with different characteristics in terms of processing, transit time and dilution. Therefore, it would be appropriate to determine the initial radon concentrations in natural gas from shale gas extraction activities. The UK has established capability to measure radon levels in various media including indoor air, water and natural gas (UKradon: PHE, 2013). It would be worth reviewing the existing radiological assessment of radon in natural gas against the parameters that might apply to shale gas extraction for reassurance purposes.

Radon contamination of water is judged unlikely to be a significant public exposure pathway, where extraction activities take place at significant depth, primarily because of the relatively long transit times that are significantly longer than the radioactive half-life of radon. However, in common with some other aspects of radon arising from hydraulic fracturing, it would be useful to have an improved evidence base of relevant field measurements, in case of future inquiries. This could be achieved if measurements of radon were to be included with other measurements that may be made of contaminants in groundwater and flowback water.

6 NATURALLY OCCURRING RADIOACTIVE MATERIALS (NORM)

6.1 Introduction

Naturally occurring radioactive materials (NORM) are materials which contain primordial radionuclides as they occur in nature, such as isotopes of radium, uranium, thorium and potassium, and the products of their radioactive decay. The presence of NORM is already well known in the oil and gas exploration and production industry: in particular, the processes by which NORM can be transported from the oil/gas reservoir to above-ground installations and onwards. The levels of NORM encountered are highly dependent on the local geology: in some cases they are no higher than those in the general environment; in other cases significant quantities of NORM are present, such that protective actions are necessary. NORM are present in the residues (cutting fluids and mud) produced by the initial drilling, although the levels are usually similar to those in the ground beneath, and are not of specific concern. Isotopes of radium (radium-226 and radium-228) and their decay products can be present in flowback water, and more specifically in the formation water, and may also be concentrated in process residues such as scales and sludges.

The potential for radon (radon-222) exposures due to releases from shale rock formations is discussed in Section 5.

6.2 Activity concentration in shale gas rock formation

Information has been published about measurements of activity concentrations of NORM in flowback water from shale gas extraction. In the US the Marcellus Shale formation is known to contain concentrations of NORM such as uranium-238 and radium-226 at higher levels than the surrounding rock formations. Some radiological data has been requested from surveys carried out for the Marcellus Shale in different areas of the Appalachian Basin (New York, Pennsylvania and West Virginia) (New York State Department of Environmental Conservation, 2011). Measurements of activity concentrations of radium-226 in drill cuttings and core samples from the Marcellus Shale were in the range 32–68 Bq kg^{-1} (0.87–1.84 pCi g^{-1}), while activity concentrations of radium-226 and radium-228 in flowback water were in the range 0.1–1.2 Bq l^{-1} (2.6–33 pCi l^{-1}) and 0.043–0.68 Bq l^{-1} (1.2–18 pCi l^{-1}), respectively (New York State Department of Environmental Conservation, 2011).

The US EPA (2012b) reported generic levels of radionuclide concentrations measured in various media (scales, sludge and produced water) in oil and gas deposits. Activity concentrations of radium in flowback water were reported to be in the range 4–3.3 10^5 Bq g^{-1}; the average activity concentration of radium (radium-226 and radium-228) in scales was reported to be 1.8 10^4 Bq kg^{-1} but could be as high as 1.5 10^7 Bq kg^{-1}. In the case of sludge, the average activity concentration of radium (radium-226 and radium-228) was reported to be 2.8 10^3 Bq kg^{-1}, while the activity concentration of lead-210 could be as high as 1.0 10^6 Bq kg^{-1}. The US EPA website also reports dose rates from contaminated equipment of 0.3–0.6 μSv h^{-1}, about five times the dose rate from natural background.

In the UK, the analysis of flowback water from exploratory drilling in Lancashire (Cuadrilla Resources Ltd at Preese Hall) by the Environment Agency (EA, 2012a) detected a number of radionuclides of natural origin, including potassium-40, lead-212 and lead-214, bismuth-214, radium-226 and actinium-228. The highest levels measured were for radium-226, with activity concentrations in flowback water of between 14 and 90 Bq l^{-1}, while activity concentrations in suspended solids were in the range of 2.5 to 7.2 Bq kg^{-1}. These values are consistent with activity concentrations of radium-226 measured in water (range 0–200 Bq l^{-1}) and soil (5–900 Bq kg^{-1}) in Europe.

6.3 Preliminary risk assessment

The statutory limit for the annual effective dose to members of the public is 1 mSv. The dose for comparison with this limit is the sum of all the doses which a member of the public receives from exposure to all regulated practices at a location. It therefore includes the summed exposure from multiple hydraulic fracturing operations and also contributions from other installations, such as a nuclear facility, located close to the shale gas field. There are also dose constraints which apply to the exposures from individual sites.

It is difficult to fully assess radiation risks to people residing in the vicinity of facilities used for the extraction of shale gas as the assessment of the radiological consequences to these people requires a detailed knowledge of the location of the facility as well as the habits of the population and the procedures used to treat and dispose of any waste containing NORM. However, some information is available on doses to workers and members of the public from NORM from oil and gas extraction. Workers involved in the offshore oil and gas industry receive doses of between a few tens of μSv a year to a few hundred μSv a year (Strand, 2004; Canoba, 2012); maximum doses of about 1 mSv y^{-1} were estimated for workers heavily involved in decontamination of separators. Doses to members of the public from the operation of a single well can be anticipated to be substantially lower. Any assessment of the radiation risks associated with NORM produced from the extraction of shale gas should distinguish between the risks associated with drilling cuttings and those with flowback water. It should also take into account the number of wells located in any single pad.

Subject to the activity concentrations present in NORM, the disposal of waste produced by a facility engaged in shale gas extraction and related activities may require an environmental permit granted under the Environmental Permitting (England and Wales) Regulations* for the accumulation and disposal of radioactive substances. The radium activity concentrations measured in flowback water are likely to warrant such a permit.

In general, such a permit would be granted subject to the results of an assessment of the radiological consequences to workers and members of the public, aimed at demonstrating that the radiation doses to members of the public from a single installation are below the relevant dose constraint of 0.3 mSv per year. However, it is expected that the waste management process will be optimised through the application of best available techniques, such that the maximum dose to a member of the public is well below this value. When evaluating permit applications it is important that the regulatory authorities should take into account the summed radiation exposures to the public from potential multiple shale gas extraction operations and, if necessary, any other sites (eg nuclear operations) potentially exposing the public to radiation, as specified in the Principles for the Assessment of Prospective Public Doses arising from Authorised Discharges of Radioactive Waste to the Environment (EA, 2012b).

* In Scotland such permits are granted under the Radioactive Substances Act 1993.

6.4 Summary

In common with other forms of oil and gas exploration and production, shale gas extraction may produce process residues and waste that contain naturally occurring radioactive materials (NORM). Many of the process residues such as drilling cuttings and fluids, scales and sludges are similar to those produced in the wider oil and gas industry, and there are established waste management arrangements for dealing with these. However, shale gas extraction also produces flowback water which may be produced in significant quantities and, depending on the geology, contain significant levels of NORM. Consequently, the site waste management arrangements need to specifically address appropriate management of flowback water (including, as appropriate, storage, treatment, transport and disposal).

Currently, the UK has no commercial shale gas extraction operations, and so there is no UK information relating to enhanced levels of radionuclides of natural origin near shale gas extraction facilities. Activity concentrations of NORM measured in flowback water and suspended solids during exploratory drilling in Lancashire were in the range of values measured in similar environmental media elsewhere in Europe. On the basis of these measurements and of the assessment of doses to workers involved in the offshore oil and gas industry, it is not expected that the extraction of shale gas would pose a significant radiological risk to the public. In addition, the existing regulatory structure in place in the UK is robust and is designed to protect the health of workers and the public from work activities involving NORM. Compliance with rigorous regulations should minimise the impact on public health from the management and disposal of NORM produced by shale gas extraction.

It would be useful for PHE to carry out a public health risk assessment prior to commercial extraction of shale gas, taking into account relevant guidance [eg Principles for the Assessment of Prospective Public Doses arising from Authorised Discharges of Radioactive Waste to the Environment and guidance published by the National Dose Assessment Working Group (NDAWG, 2012)]. This risk assessment should be based on measured levels of radioactive contamination of the flowback water and other relevant media and, where necessary, should consider the potential for multiple drilling installations to be licensed within the same shale gas field with the consequent cumulative exposure of the same population groups.

6.5 Gaps in knowledge and recommendations for further work

There is, at present, very limited data on the occurrence of NORM during shale gas extraction activities within the UK. Extrapolation from measurements made in other countries may indicate potential issues requiring regulation and/or assessment, but direct use of this data to inform UK exposure assessments is not possible owing to differences in geology, operational activities and population behaviours. An assessment of the radiological impact of the extraction of shale gas may require more detailed information on the activity concentrations of radionuclides of natural origin present in the waste produced by shale gas extraction activities in the UK. Specific measurements of activity concentrations in the materials containing NORM (flowback water, scales, sludge and brine), as well as dose rates for external exposure, are required to give reliable estimates of the possible doses received by members of the public.

In general, such an assessment could be based on generalised data for the UK; however, more specific information on the location of the facility and its proximity to habitations, as well as habit data of people living in the area, would enable PHE to estimate more accurately the radiological impact of NORM in shale formation on the local population. Information on the work practices adopted by the companies carrying out the drilling and on the processes used to treat, store and dispose of the wastes containing NORM would also be useful to perform a detailed assessment of the doses received by the workers.

7 WATER AND WASTEWATER

7.1 Introduction

This section is concerned with direct impacts of shale gas extraction on groundwater and surface water resources, and the implications for public health. It also considers the potential impacts arising from flowback water.

The process of hydraulic fracturing currently requires large amounts of water and sourcing this water may be difficult in areas where water is scarce, such as in drought or low rainfall conditions or where there are large population pressures. Finding sustainable sources of water is clearly important. In the US, options include recycling wastewater so that it can be reused and the use of saline water from deep aquifers is also being considered in some parts of the country. Alternatively, waterless fracturing fluids such as gels or gases could be used; however, more research is required to ascertain the efficiency and productivity of such types of fluids.

Disposal of flowback wastewater during shale gas extraction processes may also present potential public health risks due to the chemical constituents and large volumes of water involved. In the US, management of flowback water involves on- or off-site treatment, recycling for reuse or storage. Some operators in the US have stored flowback water on-site in man-made ponds or open pits, but stored water may be a source of surface water contamination or air pollution due to evaporation of VOCs. Additionally, evaporation can increase the concentration of dissolved substances and so further increase the potential public health risks associated with storage on-site. However, the UK regulatory approach will not permit this practice.

Storage of hydraulic fracturing fluids and flowback water on-site may lead to accidents and potential releases to the environment. There is the risk of stored hydraulic fracturing fluids and flowback water entering nearby surface water bodies or infiltrating into the soil and near-surface groundwater as a result of mismanagement of the hydraulic fracturing fluids and flowback water. Such leakage may potentially affect drinking water resources if formal accident and contingency plans are not in place (US EPA, 2012a).

Experience in the US suggests that the requirement for large volumes of hydraulic fracturing fluids may present storage issues for flowback water and may exceed the processing capacity of a site. Some operators have disposed of flowback water by injecting it back into wells which are typically depleted oil and gas wells located in areas that have porous and permeable rock strata. Other operators have processed flowback water for reuse in the hydraulic fracturing process (Schmidt, 2013). Although this may be a costly process, it reduces water use. In the US, a proportion of the flowback water has been reused, although the feasibility of reuse is dependent on salinity and the concentration of various chemical constituents accumulated during flowback. Currently, the reuse of flowback water is limited but as technology advances it is likely that the volume of flowback water that is treated and processed for reuse will increase. Developments in recycling flowback water can have great benefits in that they can reduce the burden on water sources where supplies are limited. Developments and trends in wastewater management have been reviewed in the US and it is noted that promotion of well-regulated on-site treatment technologies can reduce impacts and concerns related to waste transport and public concerns related to environmental justice and equity (Rahm et al, 2013). Flowback waters in Europe are generally expected to have high salinity owing to their predominantly marine origin, which may reduce the potential for reuse (Broderick et al, 2011).

7.2 Evidence on key pollutants and their sources

There have been no peer reviewed published investigations carried out on the impacts of shale gas extraction and related activities on controlled waters in the UK. The potential impacts of shale gas extraction and related activities on UK drinking water sources have been considered in several reviews, most notably by the House of Commons Energy and Climate Change Committee (House of Commons, 2011), the Tyndall Centre for Climate Change Research (Broderick et al, 2011) and by The Royal Society and The Royal Academy of Engineering (RS and RAE, 2012). These reviews noted that groundwater and surface water pollution had been reported in the US and also recommended appropriate regulatory control to prevent such cases in the UK. The need to demonstrate good well integrity was considered a key regulatory measure. Additionally, the last review suggests that background levels of methane in groundwater should be measured prior to shale gas extraction commencing to establish a baseline and also notes that: ‘at present, the environmental regulator does not permit shale gas extraction below freshwater aquifers’ which limits the potential for the contamination of drinking waters (RS and RAE, 2012). The British Geological Survey (BGS) has an ongoing programme measuring methane in UK groundwaters (BGS, 2012).

In the UK, the Environment Agency (EA, 2012a) has analysed flowback water from exploratory drilling by Cuadrilla Resources Ltd at Preese Hall in Lancashire. The results showed high levels of sodium, chloride, bromide and iron, as well as elevated values for lead, magnesium, zinc, chromium and arsenic compared with the local mains water that was used for injecting into the shale.

No peer reviewed published information was found on impacts on groundwater or surface waters from hydraulic fracturing activities in other European countries, though several exploratory activities are currently underway, notably in Poland. A review has been conducted by the Internal Policies Directorate of the European Parliament (European Parliament, 2011) on the impacts of shale gas and oil extraction on the environment and human health. One of the recommendations from the review was a need to reassess the European Water Framework Directive to consider the protection of water resources from accidents due to hydraulic fracturing and related activities.

A further report commissioned by the European Commission (AEA Technology, 2012a) examined the environmental risks, legislative controls and risk management options for hydraulic fracturing and related activities in Europe. In a preliminary risk assessment of all phases of hydrocarbon extraction (ie from site identification to well abandonment), groundwater and surface water impacts were considered to present the greatest threat to people and the environment. Key recommendations relating to the need to assess risks and take actions to minimise risks include the need to:

- **a** Conduct baseline monitoring of groundwater and surface water
- **b** Restrict fracturing in sensitive groundwater areas
- **c** Set quality standards for well casings
- **d** Limit pollutants in wastewater discharges and monitor any discharges
- **e** Ensure there are appropriate procedures in place to identify and manage/remediate following accidents and spills at site
- **f** Consider amendments to the Water Framework Directive and other relevant EU legislation to take account of hydraulic fracturing and related activities

There are a number of studies which have investigated the impact of shale gas extraction on water quality. Osborn and colleagues took water samples from 68 drinking water wells and reported migration of methane into aquifers, speculating that the origin was shale gas reserves (Osborn et al, 2011). This view was challenged by a series of published letters and replies (Jackson et al, 2011) and the authors noted that no evidence was found of contamination of drinking water samples with hydraulic fracturing fluids, although the testing was not comprehensive for organic chemicals or other hydraulic fracturing fluid additives. Warner et al (2012) observed migration of brine from shale gas strata to shallow waters, but noted that these occurrences did not correlate with the location of shale gas wells and were consistent with data reported before rapid shale gas development began in the region. However, the authors did suggest that the presence of the brine in shallow waters might suggest the presence of connective pathways between shale gas formations and the overlying shallow aquifer.

Further work by Warner et al (2013) on assessing groundwater impacts in the Fayetteville shale development in Arkansas had contrasting results. Assessment of groundwater samples for the presence of methane or saline solutions found no direct evidence of contamination in shallow drinking water aquifers associated with natural gas extraction. The study found no evidence for natural hydraulic connectivity between deeper formations and shallow aquifers or for gas contamination in groundwater wells located near shale gas sites. This calls into question the presence of connective pathways between shale gas formations and the overlying shallow aquifers in this area and suggests local geological conditions may influence the potential for contamination.

A study of 1,701 wells in northeastern Pennsylvania provided measurements of the prevalence and distribution of methane concentrations in groundwater, comparing levels in gas production and non-production areas (Molofsky et al, 2013). Approximately 78% of wells were found to contain elevated methane concentrations but it was concluded that shale gas extraction had not impacted on drinking water resources regionally. A further study of 141 wells within this area of Pennsylvania, assessed natural gas concentrations and isotopic signatures. Methane was identified in 82% of drinking water samples, with levels higher in homes located within 1 km of a gas well (Jackson RB et al, 2013). The elevated levels were considered to be due to poor well construction.

The most common problem with well construction is a faulty seal in the annular space around casings, which is designed to prevent gas leakage into an aquifer. The incidence rate of casing and cement problems in unconventional gas wells in Pennsylvania has been reported as 1–3.4% (Vidic and Brantley, 2013). The authors recommended improved diagnostics in cement and casing integrity for new and existing wells.

An evaluation of water sampled from 100 private wells located in close proximity to shale gas extraction sites in North Texas identified elevated levels of arsenic, selenium, strontium and total dissolved solids, and ethanol and methanol used as anti-corrosive agents, in comparison with data for reference sites outside the shale region and historic data (Fontenot et al, 2013). However, the source of contamination could not be identified and a number of wells in close proximity to extraction sites did not show elevated levels of these constituents.

The Massachusetts Institute of Technology (MIT, 2011) reviewed 43 incidents of environmental pollution related to natural gas operations (including shale) and found that almost 50% were related to the contamination of groundwater as a result of drilling operations. The most common cause of such contamination appeared to be inadequate cementing or casing into wellbores, allowing natural gas to migrate into groundwater zones as it was extracted. The review did not find any incidents of direct invasion of shallow water zones by fracture fluids migrating through fractures created during shale gas extraction. The second major cause of contamination (33%) was surface spills of stored hydraulic fracturing fluids and flowback water, which can arise from a variety of causes, including hose leaks, overflowing pits and failures of pit linings. An analysis of groundwater BTEX (benzene, toluene, ethylbenzene and xylene) following surface spills of processed water or crude oil associated with hydraulic fracturing operations identified levels that exceeded US national drinking water maximum contaminant levels (MCLs) for a number of samples; however, results also indicated that remediation actions taken by the operators after the spill were effective at reducing these concentrations (Gross et al, 2013).

These findings are consistent with incidents investigated by the US EPA (2012a) who reported the main cause of incidents to be surface spills of hydraulic fracturing fluids or flowback waters or ‘blowouts’, giving rise to uncontrolled fluid releases during construction or operation. The US EPA also identified a number of potential sources of aquifer contamination from hydraulic fracturing fluid chemicals, flowback water or released methane, other gases and volatiles, dissolved minerals or naturally occurring radioactive materials (NORM).

As a result of these incidents and the subsequent widespread public concern, the US EPA (2012a) is currently undertaking a major study of potential impacts on drinking water sources. The study will examine retrospective case studies of incidents where impacts on water resources have been reported and prospective case studies potentially involving the use of chemical tracers to track the fate and transport of injected fracturing fluids. The study will also analyse existing data on the toxicity of the chemicals used in the processes as well as study some naturally occurring substances that have no existing toxicological data. The findings are expected to be published in 2014.

Regarding the impact arising from the disposal of wastewaters, recent papers have noted the need for appropriate treatment prior to discharge to the environment. An analysis of effluent samples collected from the outfalls of wastewater treatment works in Pennsylvania identified higher than background levels of a number of analytes following discharge, including barium, strontium, bromides and benzene, and noted the need for monitoring to characterise wastewater streams (Ferrar et al, 2013b; Warner et al, 2013). Contamination of Ohio river tributaries with barium, strontium and bromide has also been reported (Voltz et al, 2011) following discharge of flowback water after processing at water treatment works. The authors further considered that the bromide content could increase disinfectant byproduct (DBPs) formation in chlorinated drinking water supplies. A study of effluent discharged from wastewater treatment plants, which had accepted wastewater from both conventional and unconventional oil and gas extraction activities in Pennsylvania, concluded that the effluent contained a greater amount of DBPs including brominated DBPs (Hladik et al, 2014). Effluents were found to have a unique DBP signature when compared with effluent from treatment plants not accepting wastewater from these activities.

Additional concerns have been raised regarding the use of diluted treated hydraulic fracturing wastewater (THFW) for crop irrigation as is the practice in some US states (Shariq, 2013). While only limited data has been presented in the literature on the impact of this disposal route, the practice is unlikely to be permitted in the UK without considering the long-term implications for the environment and human health.

7.3 Preliminary risk assessment

Based on the information obtained to date, there are a number of shale gas extraction activities that may impact on surface and groundwater and hence have the potential to impact upon drinking water quality:

- **a** Production and storage of hydraulic fracturing fluid and flowback water on-site and the possibility of spills from stored chemicals which may percolate to subsurface aquifers or may enter surface watercourses
- **b** Well blowout during well completion resulting in contamination of surface waters and also possible impacts on groundwater
- **c** Use of hydraulic fracturing fluids and possible contamination of aquifers during injection and flowback if well integrity is not maintained
- **d** Release of volatiles during hydraulic fracturing and the possibility of methane and other gases reaching aquifers through poor well integrity and/or through fissures in the strata
- **e** Accidents or spillages during transportation of wastewaters off-site and improper waste treatment prior to discharge, which may result in possible contamination of surface waters
- **f** Water resource and acquisition since large volumes are required for borehole drilling and hydraulic fracturing (not being considered in this evaluation)

Experience in the US suggests that the greatest risk of contamination of water sources is posed by the potential for surface spills of chemical additives (Energy Institute, University of Texas, 2012). Modelling of environmental risk using probability bounds analysis indicates that waste management of spent fracturing fluids presents the largest risk of environmental contamination (Rozell and Reaven, 2012). Research studies so far have not identified the presence of hydraulic fracturing fluids in groundwater; but methane, possibly originating from shale beds, has been detected in aquifers, indicating potential problems with well integrity.

Concerns have been raised based on incidents reported in the US of the potential for drinking water supplies to become contaminated with chemicals and other substances arising from shale gas extraction and related activities. In the UK, drinking water originating from surface sources (eg reservoirs, lakes and rivers) or from groundwater (aquifers accessed by boreholes) undergoes some treatment. Around 99% of water supplied in England arrives at consumers' taps under the management of water companies. These public water supplies are checked against a number of water quality parameters, with compliance based on measurements on water leaving water treatment works as well as measurements on random samples taken in consumers' homes. Water quality issues in the US have generally arisen in remote areas where water is supplied by privately accessed boreholes for which there may be minimal and variable treatment of the supply and very limited testing of water quality. It is difficult to foresee such eventualities arising in the UK, given that the majority of drinking water is supplied from public water supplies which have a high level of regulatory control and testing.

The potential for shale gas extraction and related activities to impact on public drinking water supplies is considered minimal as the Water Supply (Water Quality) Regulations 2010 provide for the protection of the public from any substance or organism likely to cause a threat to public health. The regulations require water companies to assess risks to their supply systems, identify any potential hazards and have appropriate mitigation measures in place. Local authorities will also need to consider the implications for their risk assessments of private water supplies.

Around 1% of the UK population receives their water from private water supplies which may receive minimal treatment and testing (DWI, 2012). These supplies are particularly vulnerable to pollution and, as a result, it would be expected that the presence of private water supplies as well as overlying aquifers would be a material consideration in approving shale gas operations. Consideration should be given to developing analytical techniques capable of detecting contaminants which might arise from shale gas extraction and related activities and for applying these analytical methods as part of environmental water quality assessments.

A number of mitigation and control measures may be identified from experiences in the US and elsewhere. These mitigation measures can be summarised as follows:

- **a** Site management, bunding and storage and inventory control of chemicals and fuels on-site
- **b** Maintenance of well integrity throughout its lifetime: well design, construction and abandonment according to best practice
- **c** Full disclosure of chemicals used in hydraulic fracturing fluids
- **d** Monitoring of sensitive aquifers for specified chemicals
- **e** Development of appropriate analytical detection methods for chemicals used in hydraulic fracturing and related activities including waste products
- **f** Development of environmental quality standards where these do not exist
- **g** Containment of any expelled materials from 'blowouts' and appropriate clean-up procedures
- **h** Warnings to users of any affected surface waters and restriction of access
- **i** Interception and remediation of surface spills and leaks before they impact on drinking water supplies and/or provision of advice to consumers
- **j** Regulatory controls on treatment works receiving wastewaters from shale gas extraction activities

Where appropriate and relevant, these control measures should be included in the permitting and operational consents granted by the principal regulatory bodies.

A recent publication by the Chartered Institute of Water and Environmental Management (CIWEM, 2014) concurs with the above proposed mitigation and control measures, noting the need for baseline data before shale gas activities commence and long-term monitoring throughout the lifetime of the well; consideration of the potential for wellbore failure, and the need for best practice in well construction and rigorous well testing; transport, management and storage of chemicals, hydraulic fracturing fluid and flowback water; treatment of flowback water; and best practice management to minimise spills and leaks. Additionally, CIWEM (2014) recommended that exploration should not be permitted in areas where there is a risk to groundwater, and there is a need for a detailed risk assessment to examine the relationship between the shale and the aquifer.

A recent memorandum of understanding (MoU) signed by Water UK, which represents the water industry, and the UK Onshore Operators Group (UKOOG), aims to ensure respective members work together to help minimise the impact of onshore oil and gas developments on local water and waste services in the UK (Water UK, 2014). Under the MoU members will work together to identify and resolve risks around water or wastewater, which will include baseline monitoring requirements to assess the impact of developments on water resource quality and quantity, and plans related to site water management and wastewater disposal.

There have been reports of hydraulic fracturing fluid contaminating groundwater, but this appears to be less to do with the hydraulic fracturing process and more likely the result of either catastrophic or progressive well failure resulting in leakage of hydraulic fracturing fluid or flowback water. Examples include poor cementation which allows fluids to move vertically through the well casing or between casings and rock formation or radial leakage where poor well casing construction allows fluid to move horizontally out of the well and migrate into the surrounding rock strata.

Contamination arising from the fracturing process does not appear to be a significant issue since the length of the fracture is relatively short compared to the depth of the well and overlying rock. Vertical well sections may be drilled hundreds to thousands of feet below the land surface and lateral sections may extend 1,000 to 6,000 feet (300 to 2,000 m) away from the well. The majority of fractures may be only a few micrometres in width and are usually limited in length to a few tens of metres (US EPA, 2012a). The likelihood of hydraulic fracturing fluid reaching underground sources of drinking water through fractures is reported to be remote where there is a separating impermeable layer of at least 600 m between the drinking water sources and the production zone (AEA Technology, 2012a). Data from fracture mapping technologies on thousands of hydraulic fracturing treatments has indicated that induced vertical fracture heights do not exceed ‘tens to hundreds of feet’, and are therefore unlikely to be a concern from a groundwater contamination perspective (Fisher and Warpinski, 2012). In addition, the flow of hydraulic fracturing fluids will be inhibited by a range of factors, such as capillary tension, leading to sequestering of the fluids, preventing upward movement towards shallow groundwater (Engelder, 2012).

The weight of evidence is that fracture propagation ‘out of zone’ to shallow groundwater is unlikely from deep (1000 m or 3000 ft) shale gas reservoirs; however, this may not be true at shallower depths and consideration is needed of cross-connections between wells, including abandoned wells, in neighbouring areas which could provide migratory pathways (Jackson RE et al, 2013). The authors recommended the need for baseline geochemical mapping and groundwater monitoring systems as well as appropriate field testing.

Contamination from the fractures is not expected to be a viable risk to groundwater and there is no unequivocal evidence of chemicals entering local aquifers and groundwater from the actual fracturing process. The presence of aquifers should be a key consideration in the siting of any wells in the UK.

Planning and other regulatory and site operational controls, including high quality well integrity, appropriate storage of hydraulic fracturing fluids and flowback water, and good environmental management of surface and below-ground activities, should protect water sources from any adverse impacts resulting from shale gas extraction and related activities. However, the potential for accidents will require effective incident management procedures and appropriate planning will be required.

7.4 Gaps in knowledge and recommendations for further work

Appropriate monitoring of aquifers and surface waters is needed to assess exposure and should be a critical part of any risk assessment process. Baseline monitoring data is required before drilling to establish background levels of pollution and any monitoring programme will need to continue throughout the lifetime of the well, including the decommissioning of the well pad. Analytical methods may need to be developed that are capable of detecting chemicals associated with shale gas extraction and related activities. There is a need to consider private or concessionary abstractions close to fracturing activities and to examine the best ways of protecting the sources of these supplies. Water safety plans may offer some potential in this regard.

Shale gas extraction and related activities have the potential to mobilise natural contaminants and minerals and these will vary according to the geology of the area. There is a need to characterise these contaminants on a case-by-case basis. Agencies in the UK will need to agree criteria for correct disposal of wastewater after treatment via regulation and permitting regimes.

8 HYDRAULIC FRACTURING FLUID

8.1 Introduction

During the hydraulic fracturing process water is pumped at high pressures into the shale. Shale gas operations use a range of oil and water based fluids and treatments to allow efficient injection into the well, induce and maintain permeability, and generate productive fractures. To improve the efficiency of the hydraulic fracturing process chemicals are often added to the water to create hydraulic fracturing fluid. These chemicals have a number of roles. For example:

a Proppants keep induced fractures open
b Biocides prevent bacterial growth, which can impact on the gas well’s productivity
c Surfactants reduce surface tension aiding fluid recovery
d Polymers reduce friction between the hydraulic fracturing fluid
e Corrosion inhibitors

The composition of hydraulic fracturing fluids is dependent on a number of factors such as the underlying geology, the type of rock to be hydraulically fractured and operational considerations. They typically vary from operator to operator. Specialised vehicles and containers are required to transport and store hydraulic fracturing fluids or the component chemicals. Table 1 lists the main components of hydraulic fracturing fluid reported in the US and their roles. Hydraulic fracturing operators in the UK intend to publicly disclose the chemical additives of fracturing fluids (UKOOG, 2013a).

TABLE 1 Main reported components of hydraulic fracturing fluids used in the US (Committee on Energy and Commerce, 2011; US EPA, 2004)

Additive type	Main compound(s)	Purpose	Common use of main compound
Acids	Formic and hydrochloric acids	Used to dissolve the rock and create a conduit	Used in cleaning products
Acid corrosion inhibitors	Acetone	Required in acid fluid mixtures because acids will corrode steel tubing, well casings, tools and tanks	Used in pharmaceuticals, fibres and nail polish remover
Biocides, bactericides or microbiocides	Gluteraldehyde	Used to kill any existing microorganisms such as bacteria and algae, and to inhibit bacterial growth and deleterious enzyme production	Disinfectant, sterilisation of medical and dental equipment
Breakers or breaking agents	Ammonium persulphate, ammonium sulphate, copper compounds, ethylene glycol and glycol ethers. Also includes metal-ion-cross-linked guar such as chromium, aluminium and titanium	Used to break the cross-linker and eventually the polymer. Also used to degrade hydraulic fracturing fluid viscosity	Bleaching agent in detergents and the production of plastics
Diesel fuel	Petroleum product	Delivery system sometimes used to dissolve guar gum or guar based derivatives	Fuel for vehicles
Foamed gels	Employ nitrogen or carbon dioxide as their base gas. Also contain diethanolamine and alcohols such as isopropanol, ethanol and 2-butoxyethanol	Foam bubbles to transport and place proppant into fractures	Shaving foams, shampoos and creams
Fluid-loss additives	Mixture of natural gums, resins and bridging agents	Restrict leak-off of the fracturing fluid into the exposed rock at the fracture face	–
Friction reducers	Typically latex polymers or copolymers of acrylamides	Used to minimise friction	Water treatment and soil conditioner
Gels	Guar gum, guar derivatives such as hydroxypropylguar or cellulose derivatives such as carboxymethylcellulose	Creates higher viscosity fracturing fluids to transport the proppant	Cosmetics, toothpastes, baked goods and ice cream
Iron control	Citric acid	Prevents the precipitation of metal oxides	Food additive, flavouring in food and beverages and lemon juice
Oxygen scavenger	Ammonium bisulphate	Removes oxygen from the water to protect the pipe from corrosion	Cosmetics, food and beverage processing
Ph adjusting agent	Sodium or potassium carbonate	Maintains the effectiveness of other components	Washing soda, detergents, soap and water softener
Proppant	Silica-quartz sand	Used to prop open a hydraulic fracture	Drinking water filtration, play sand and bricks
KCl salt	Potassium chloride	Used to increase viscosity and increase proppant transport capacity	Low sodium table salt
Surfactant	Isopropyl alcohol	Used to increase stability of fracture fluid	Glass cleaner, antiperspirant and hair colour

8.2 Evidence on key pollutants and sources

Currently, there is no published peer reviewed literature in the UK on the likely composition and use of hydraulic fracturing fluids. There is limited data on hydraulic fracturing fluid composition from UK operations. The composition of hydraulic fracturing fluids used by Cuadrilla during hydraulic fracturing activities in Lancashire has been disclosed. Water and sand accounted for 99.75% of the hydraulic fracturing fluid volume, with polyacrylamide friction reducers (0.075%), hydrochloric acid (0.125%), an unnamed biocide (0.005%) and sodium salt (0.00005%), which acts as a tracer, accounting for the rest (Cuadrilla, 2011).

The Royal Society and The Royal Academy of Engineering (RS and RAE, 2012) have recommended a number of measures to protect groundwater from hydraulic fracturing fluid, while the House of Commons Energy and Climate Change Committee (House of Commons, 2011) recommended that the EA monitor flowback water to assess potentially harmful materials. They also recommended that monitoring of groundwater should be undertaken before, during and after hydraulic fracturing operations to allow for a full assessment of any potential contaminants.

The UK Onshore Operators Group (UKOOG) that represents the industry has developed onshore shale gas well guidelines which state that operators must publicly disclose all chemical additives to fracturing fluids on a well-by-well basis, including regulatory authorisations, safety data and maximum concentrations and volumes (UKOOG, 2013b).

In the UK, as in other EU member states, the Water Framework Directive and the Groundwater Daughter Directive protect groundwater against pollution by preventing or limiting the entry of pollutants to groundwater. The Directive requires that hazardous substances must be prevented from entering groundwater, and the input of non-hazardous pollutants must be limited to ensure that groundwater does not become polluted.

The agencies responsible for groundwater protection in the UK are the Environment Agency in England, Natural Resources Wales, the Scottish Environment Protection Agency and the Northern Ireland Environment Agency. These agencies are responsible for considering whether a potential pollutant should be determined as a hazardous substance or a non-hazardous pollutant . These assessments are reviewed by the Joint Agencies Groundwater Directive Advisory Group (JAGDAG) whose role it is to advise on the determination of the status of substances. JAGDAG comprises the agencies noted above together with the Department for Environment, Food and Rural Affairs (Defra), Welsh Government (WG), the Environmental Protection Agency Ireland (EPA), and Public Health England (specifically the PHE Centre for Radiation, Chemical and Environmental Hazards) as well as industry representatives. The JAGDAG assessments are subject to public consultation and may be subject to further review before a final determination is made. JAGDAG will review the assessment of hydraulic fracturing fluid components to ensure that any chemicals are properly risk assessed prior to use in the UK.

Owing to commercial confidentiality there was, until recently, little disclosure of the chemical composition of hydraulic fracturing fluids in the US. With the exception of state-specific laws, companies are not mandated by federal regulations to disclose the identities or quantities of chemicals used. Disclosure is voluntary, leading to concerns associated with accuracy and completeness of reported information, and the ability to determine whether chemicals have the potential to impact on health and the environment (Maule et al, 2013).

The Fracturing Responsibility and Awareness of Chemicals Act (FRAC Act) (S.587–112th Congress (2011) requires companies to disclose details of the components of hydraulic fracturing fluid, although not the proprietary formula. In 2011, the US Committee on Energy and Commerce launched an investigation into hydraulic fracturing in the US (Committee on Energy and Commerce, 2011). The Committee requested 14 leading oil and gas service companies to disclose the types and volumes of the products they used in their hydraulic fracturing fluids between 2005 and 2009 and the chemical contents of those products. This report contained a list of over 2,500 hydraulic fracturing products containing 750 chemicals and other components. This exhaustive list contained chemicals that are relatively harmless, such as salt and citric acid, but also substances of more concern, such as BTEX (benzene, toluene, ethylbenzene and xylene). Table 2 summarises the main components reported to the Committee.

TABLE 2 Main chemical components used in hydraulic fracturing fluid in the US between 2005 and 2009 (Committee on Energy and Commerce, 2011)

Chemical component	Number of products containing chemical
Methanol (methyl alcohol)	342
Isopropanol (isopropyl alcohol, propan-2-ol)	274
Crystalline silica-quartz (SiO_2)	207
Ethylene glycol monobutyl ether (2-butoxyethanol)	126
Ethylene glycol (1,2-ethanediol)	119
Hydro-treated light petroleum distillates	89
Sodium hydroxide (caustic soda)	80

In addition to the Committee's report, there have been other reviews into the composition of hydraulic fracturing fluids and the potential risks associated with the chemicals used in hydraulic fracturing fluids. Colborn et al (2011) reviewed the toxicity of 353 chemicals through literature searches and material safety data sheets and found that 75% of the chemicals reported could affect dermal, ocular, respiratory and gastrointestinal systems, while approximately 40–50% of the chemicals could affect the nervous or immune systems. In addition, 37% of the chemicals reported could affect the endocrine system, and 25% were potential carcinogens or mutagens. Information on the remaining chemicals was not obtained due to lack of full disclosure and appropriate Chemical Abstract Service (CAS) number identification. The authors concluded that, despite the relatively small amounts of these chemicals in the overall hydraulic fracturing fluid, the potential health impact of such chemicals warrants full disclosure of all chemical products, strict regulation and comprehensive air and water monitoring.

Kassotis et al (2013) detected endocrine disrupting activity (oestrogenic, anti-oestrogenic or anti-androgenic activity) in an *in-vitro* test system for a selection of 12 chemicals used in natural gas extraction in the US. Endocrine disrupting activity was also detected in groundwater and surface water considered to have been contaminated by fluids/wastewater from natural gas extraction processes (ie from spills/leaks), again using an *in-vitro* test system.

The authors suggested that the reported endocrine disrupting activity of the chemicals used in natural gas extraction may have contributed to the endocrine disrupting chemical activity detected in the water samples, ie in areas where contamination spills of fluids/wastewater used in gas extraction may have occurred. This is a single study showing a relatively weak response in *in-vitro* assays.

It is important to note that endocrine disrupting activity detected in an *in-vitro* test system does not necessarily mean that an adverse health effect will occur *in vivo* (in a whole organism). For example, the levels of exposure producing an effect *in vitro* may be insufficient to produce an adverse effect in animals or humans. However, *in-vitro* tests for endocrine disrupting chemical activity are useful as an initial screen for prioritising further toxicity testing and providing information on the potential mode of action. In the EU it is expected that REACH test methods for assessing endocrine disrupting classification (using *in-vivo* tests) are expected to be available by the end of 2014. It is also useful to note that the chemicals used in the US may not be the same as those proposed for use in the UK and that chemicals used in natural gas extraction in the UK would have to be assessed by the environmental regulators and assessed by JAGDAG.

In Canada, the province of New Brunswick has announced that companies will be required to make a full disclosure of all chemicals used in hydraulic fracturing fluid. A report by the Chief Medical Officer of Health (Office of the Chief Medical Officer of Health, 2012) went further and recommended that the requirement for disclosure should cover all chemicals used by the shale gas industry, and be publicly available and disclosed in a timely fashion and with sufficient lead time to be included in human health and environmental risk assessments.

8.3 Summary

Experience from the US highlights the wide variety of chemicals which have been used during hydraulic fracturing operations. The composition of hydraulic fracturing fluids will vary dependent on factors including underlying geology, operational requirements and operator preference. Recent developments in the US have put the emphasis on transparency of reporting and full disclosure of chemical additives.

Although the concentration of individual chemicals in the hydraulic fracturing fluid is low, the amount of hydraulic fracturing fluid that is required means that the volumes of chemicals required, which may also need to be stored on-site, could be significant. The quantity and concentration, route of exposure and eventual fate will determine the level of risk associated with the chemicals. It is, therefore, strongly recommended that any chemicals that are used are fully disclosed and subject to independent assessment prior to use. JAGDAG will peer review the classification of hydraulic fracturing fluid components, to ensure chemicals are appropriately risk assessed prior to use.

As discussed in Section 7, well design and construction is an integral part of controlling the risk from leakage of hydraulic fracturing fluid. Well integrity is vital in order to prevent contamination of groundwater and surface waters.

Accidents from surface activities such as handling and processing of hydraulic fracturing fluids and surface or subsurface blowouts, as reported in the US, can cause contamination of groundwater and surrounding land. Such incidents can be prevented through the implementation of control measures and best practice when storing, handling and processing hydraulic fracturing fluids, and associated waste materials. Accident management plans and strict enforcement by regulatory bodies will further reduce the risk of accidents. Evidence from the US suggests that many of the chemicals used to produce hydraulic fracturing fluids are mixed on-site. This requires chemicals to be stored and handled in a concentrated form and good on-site management and plans are needed to minimise the risk to workers, the public and the environment.

8.4 Gaps in knowledge and recommendations for further work

There are significant gaps in the literature about the identities and quantities of the chemical components of hydraulic fracturing fluids, with the majority of available data based on activities in the US. It is likely that the composition of hydraulic fracturing fluids used in UK will be different to those used in the US. Full disclosure of the chemicals within the hydraulic fracturing fluid is a critical part of any risk assessment process, which will be supported through peer review by JAGDAG. Additionally, this will allow better understanding of the technologies required to adequately treat and process hydraulic fracturing fluids for reuse. A comprehensive regulatory framework at the permitting and planning stage is required in the use, handling and disposal of hydraulic fracturing fluids.

As noted in Section 7, there is a need for baseline monitoring of aquifers and surface water prior to hydraulic fracturing and related activities, as well as continuing monitoring during exploration, production and well abandonment. Any monitoring programme needs to include materials associated with shale gas extraction including chemicals used in the hydraulic fracturing fluid.

Chemical handling and storage of hydraulic fracturing fluids should adhere to clear and robust guidelines to minimise the potential for accidents and potential releases into the environment. Formal accident and contingency plans will allow for appropriate and timely response to any eventuality.

9 ROLE OF HEALTH IMPACT ASSESSMENT

If commercial-scale shale gas developments are considered, it is important to determine how best to evaluate health issues prior to operation. There are a number of potential tools and methods that could look at the health impact of shale gas extraction and related activities, eg human health risk assessment, environmental impact assessments or strategic environmental assessments. Health impact assessment (HIA) has broad applicability, considering both adverse and beneficial health effects, through incorporation of various types of evidence, and its emphasis on stakeholder participation. In New Brunswick, Canada, the Chief Medical Officer of Health (Office of the Chief Medical Officer of Health, 2012) made a number of recommendations concerning shale gas development including a commitment to use HIA as a tool in the regulatory process to protect health from changes in both the social and physical environments.

A research group based at the Colorado School of Public Health (Colorado School of Public Health, 2011; Witter et al, 2013) has published a wide-ranging health impact assessment (HIA) on the impact on a local community of a large shale gas development potentially incorporating up to 200 individual gas wells. This HIA considered a wide range of issues from the impact of emissions to air, land and water, noise and visual impact, transportation to and from the site, the health profile of the local community, economic benefits and broader social issues such as the impact of the influx of workers on the infrastructure of the local community. The HIA made a number of recommendations, including the need for air quality monitoring, and clear thresholds at which operations would be shut down to regulate the industry as well as mechanisms for health monitoring. The importance of using best available technology and best management practices to reduce air emissions to as low as possible was emphasised.

The study also identified potential risks related to chemical exposures, accidents, psychological impacts (such as depression, anxiety and stress) and social impacts, and proposed over 70 recommendations for minimising the risks.

Witter et al (2013) followed this comprehensive HIA with a review of the use of HIA in communities undergoing natural gas development. Among the lessons learnt were the need for any HIA to be impartial, based on evidence, open to highlight positive impacts of development and free of the constraints of political pressure.

A major epidemiological study is being set up in the Marcellus Shale region of central Pennsylvania and southern New York state. A major aim of the project is to develop a cross-disciplinary, integrated repository of shareable environmental, health and community data to facilitate further investigations (Geisinger, 2013).

At present there is no development on such a scale planned for the UK but should commercial-scale gas extraction operations be planned, HIA may be considered as a useful tool to assess the impact on public health of shale gas extraction and related activities.

HIA has been used to assess a range of policies, plans and individual projects (such as planned industrial facilities) in the UK. HIAs may be undertaken by consultants for industry to determine the potential impact of their proposals and these may also be subject to review by other agencies such as local public health professionals. Often the methods used in an HIA form part of other impact assessment strategies, such as strategic environmental assessments (SEA) or environmental impact assessments (EIA).

While the Colorado HIA is the only comprehensive, published HIA, other health impact studies have considered specific issues associated with shale gas extraction and related activities such as the chemicals used in hydraulic fracturing fluid and drinking water impacts. Regarding the latter, the US EPA is currently conducting a study to better understand any potential impacts of hydraulic fracturing on drinking water and groundwater.

The boundaries for an HIA or any other form of impact assessment such as an SEA for shale gas development and production would need careful definition and design. The objectives of an HIA would differ on a case-by-case basis, depending on the definition of health used, the type of development, the scale of the operation, the availability of data and the specific health outcome or issue under consideration. Lack of data and information may make an HIA difficult. As is clear in this report, accurate data on likely exposures and impacts is limited or not yet available.

HIAs can often be time and resource intensive; depending on their scope they can take months or even years. The scale and size of the development under consideration are also key factors since an HIA around a single drill site may have limited value. Therefore the potential of HIA to assess shale gas activities remains to be determined and HIA may not be needed for all developments. The US National Academy of Sciences (National Research Council, 2014) has recently discussed the potential value of HIA for new shale gas developments, while in the UK, HIA has been typically used to assess the impact of large-scale developments or strategic policies and plans (eg waste management facilities). Clearly, health impacts of shale gas developments will need to be thoroughly assessed and HIA offers one tool to assess the health consequences of such developments. Consideration should be given to integrating the principles and methods of HIA early on in the planning process.

10 SUMMARY

This review has focused on the impact of direct releases of chemicals and radioactive material from shale gas extraction and related activities. The review was conducted to underpin PHE's duty to provide specialist advice to those responsible for public health protection, including local authorities and regulators. The scope of the review was limited to an assessment of the public health impact due to emissions and potential chemical and radiation exposures associated with shale gas exploration and extraction, considering likely operational practice in the UK. Other considerations, such as water sustainability, noise, traffic (apart from vehicle exhaust emissions), odour, visual impact, occupational exposure and wider public health issues, have not been addressed. However, should commercial-scale shale gas extraction be introduced, such issues will need careful evaluation on both a national and local scale.

This review provides an assessment of the potential risks from emissions of chemical and radiological pollutants due to shale gas extraction activities, based on the likelihood of harm resulting from exposure to the hazard. A common model for assessing risks is the source-pathway-receptor model in which hazards are identified, such as potential contamination of air or water (source), allied to consideration of their fate and behaviour in the environment (pathways) and the presence of any populations that may be exposed (receptors). The review has detailed the potential hazards from emissions of chemical and radiological pollutants and, where data is available, evaluated the associated risks.

Hazards to health from shale gas extraction activities include potential emissions to air of primary pollutants such as oxides of nitrogen (NO_x) or particulate matter (PM) and the precursors of secondary pollutants such as O_3 and volatile organic compounds. Shale gas extraction activities may also impact on surface water and groundwater through accidents and spillages. Most evidence suggests that contamination of groundwater as a result of borehole leakage through poor well design, construction and integrity is an area of concern, but that contamination of groundwater from the underground hydraulic fracturing process itself is unlikely. There is also a need to adequately manage the chemicals used in hydraulic fracturing fluids as well as the process residues and waste containing chemicals and naturally occurring radioactive materials (NORM).

The risks from small-scale drilling for exploratory purposes (eg single wells) are clearly different from the risks from commercial-scale operations. The potential health impact from single wells is likely to be very small, but the cumulative impacts of many wells in various phases of development in relatively small areas are potentially greater and will need careful scrutiny (AMEC, 2013), during the planning process. It would be appropriate to determine the initial radon concentrations in natural gas from hydraulic fracturing sources as well as the radiological activity concentrations in the NORM-containing waste materials to provide adequate reassurance. Baseline environmental monitoring data for emissions to air and water are required before drilling to establish background levels. This is already underway for methane in groundwater (BGS, 2012). Any monitoring programme will need to continue throughout the lifetime of the well, including the decommissioning of the well pad. Analytical methods may need to be developed that are capable of detecting chemicals associated with shale gas extraction and related activities. Agencies in the UK will need to agree criteria for correct disposal of wastewater after treatment via regulation and permitting regimes.

Experiences from countries with commercial-scale operations, particularly the US, demonstrate that good on-site management and appropriate regulation of all aspects of the operations, from exploratory drilling to gas capture and well abandonment, as well as the use or storage of hydraulic fracturing fluid and the treatment of any wastes, are essential to minimise the risk to the environment and public health. Well-publicised problems in the US appear to be attributable to operational failures and inadequacies in the regulatory environment. The geology, topography, mode of operation and, most importantly, the regulatory environment will be significantly different in the UK. The UK has an established onshore oil and gas industry and, although shale gas extraction is a relatively new process and there is limited experience of its use in the UK, the potential emissions and many of the associated industrial processes (such as horizontal drilling or the use, transport and processing of chemicals) are not new and their risks are relatively well characterised.

UK and EU regulatory frameworks have outlined a range of mitigation measures that have been identified to control and minimise the release of any potential pollutants and to ensure that the public is protected from exposure. The UK’s planning and regulatory approaches are intended to allow for public consultation during the development process and public health agencies including PHE are consulted on environmental permit applications, enabling assessments of the potential risks to health to be undertaken. It is essential that they are applied robustly to the shale gas extraction process and that health impacts of operations are therefore assessed. Operators and developers will also be required to use best available techniques and good industry practices to prevent, manage and reduce the impacts and risks associated with shale gas exploration and production projects and the industry should be transparent in its operations and constantly improve technologies and operating practices.

At present there is limited environmental and health surveillance data within the published literature in relation to existing shale gas extraction operations. There have been very few epidemiological studies and those that have been carried out generally lack robust exposure assessments. A few studies have suggested associations between adverse health impacts and shale gas extraction activities; however, the authors have highlighted a number of limitations within these studies and it is evident that further work is required. The UK has an opportunity, in advance of significant development of shale gas extraction activities, to consider appropriate environmental and epidemiological studies to strengthen the evidence base on potential health impacts. However, the challenge for any investigation is that potential emissions associated with shale gas extraction activities are generally common to a number of other sources, such as industry and traffic, making it difficult to clearly attribute any exposures to shale gas extraction activities.

In conclusion, the currently available evidence indicates that the potential risks to public health from exposure to the emissions associated with shale gas extraction will be low if the operations are properly run and regulated. In order to ensure this, regulation needs to be strongly and robustly applied.

11 RECOMMENDATIONS

Further work will be required to define better the potential health impact of shale gas extraction. The drilling of exploratory wells should allow the collection of a comprehensive set of data on shale gas extraction and related activities. This data should contribute to an improved evidence base to inform UK risk assessments. Health impact assessments or similar approaches are a means of assessing the wider impacts of shale gas extraction and related activities on both a local and regional scale.

Each section has identified a number of gaps in knowledge and potential areas for further work. A number of key areas for further work are proposed:

- **a** Public Health England needs to continue to work with regulators to ensure all aspects of shale gas extraction and related activities are properly risk assessed as part of the planning and permitting process
- **b** Baseline environmental monitoring is needed to facilitate the assessment of the impact of shale gas extraction on the environment and public health. There should also be consideration of the development of emission inventories as part of the regulatory regime
- **c** Effective environmental monitoring in the vicinity of shale gas extraction sites is needed throughout the lifetime of development, production and post-production
- **d** It is important to ensure that broader public health and socioeconomic impacts such as increased traffic, impacts on local infrastructure and worker migration are considered
- **e** Chemicals used in hydraulic fracturing fluid should be publicly disclosed and risk assessed prior to use. It is useful to note that any potential risk to public health and the environment from hydraulic fracturing chemicals will be dependent on the route of exposure, total amount and concentration, and eventual fate of any such chemicals. It is expected that these aspects will be considered as part of the regulatory environmental permitting process
- **f** The type and composition of the gas extracted is likely to vary depending on the underlying geology and this necessitates each site to be assessed on a case-by-case basis
- **g** Evidence from the US suggests that the maintenance of well integrity, including post-operations, and appropriate storage and management of hydraulic fracturing fluids and wastes are important factors in controlling risks and appropriate regulatory control is needed
- **h** Characterisation of potentially mobilised natural contaminants is needed including naturally occurring radioactive materials (NORM) and dissolved minerals

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