Considerations for quantifying fugitive methane releases from shale gas operations

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Miranda Kavanagh

Director of Evidence

Foreword

This report has been produced to inform the Environment Agency about the options available for quantifying the amounts of fugitive methane released to air from certain onshore oil and gas operations. The emphasis is on exploratory operations to extract methane from shale by hydraulic fracturing - commonly known as 'shale gas operations' (as in the title). Hydraulic fracturing for shale gas is one example of using 'unconventional' methods to extract gaseous hydrocarbons. Similar considerations for quantifying fugitive methane apply to other 'unconventional' exploratory operations (e.g. for coal-bed methane), so the report is relevant to 'unconventional gas' operations in general. The report focuses on methods for monitoring fugitive methane, and on proposing monitoring efforts that are proportionate to a site's characteristics and environmental risks.

There are several reasons for quantifying fugitive releases of methane. These include reporting of emissions, assessing health and environmental impacts, and determining if emission controls are needed or effective. Most quantitative estimates of fugitive releases are ultimately based on measurements made at or near sources. However, it may not be necessary to make emission measurements at every source situation. This is because if enough representative measurements are available for a given situation they may be used to derive generic emission factors for estimating emission quantities in similar situations, so reducing the need for extra measurements.

The onshore unconventional gas sector is an emerging industry in the UK, rather than an established one. Consequently, there is a shortage of representative and detailed measurements of fugitive methane releases under UK conditions. In order to address this shortage, more representative and detailed measurements are needed for the sector, including measurements that can be used to derive generic emission factors. This need was noted in a recent Department of Energy and Climate Change (DECC) report (2013, edited by MacKay and Stone) which recommended there should be a detailed scientific research programme of methane measurement.

In view of the need for methane measurements, the present report emphasises the types of detailed measurement methods that are available to quantify fugitive methane emissions. The methods are presented as a hierarchy of techniques that can be used in line with the risks to the environment and the performance of an operator at a site. While more approximate and cheaper methods may be acceptable in situations with lower risks and higher performance, more detailed and costly methods may be appropriate in situations with higher risks and variable performance. The hierarchy can be used to select simpler methods for basic surveillance purposes, and more sophisticated methods for detailed studies e.g. for calibrating generic emission factors.

Work on the report has spanned nearly all of 2013. During this period there have been several practical and technical developments in the UK's approach to regulating oil and gas operations – which include shale gas exploration and production. For example, in June 2013 the Environment Agency converged its approaches for 'conventional' and 'unconventional' operations, so that the previous distinct approaches were harmonised in a new unified oil and gas extraction sector. The main focus of the work is on how a hierarchy of monitoring regimes for fugitive methane could be developed and applied on a risk basis; the potential for generic factors to be used for quantifying emissions is also briefly considered.

The report is not a statement of the Environment Agency's position and it does not represent Environment Agency guidance on the matter.

Executive summary

The use of hydraulic fracturing to explore for shale gas is one example of using 'unconventional' methods to explore for gaseous hydrocarbons. Such exploratory operations are likely to arise in UK over the coming years, and are expected to include exploration for both shale gas and coal bed methane. The Environment Agency is the environmental regulator for shale gas and similar 'unconventional' gas operations in England. From April 2013, Natural Resources Wales (NRW) took over the corresponding functions previously carried out by the Environment Agency in Wales.

Operators who intend to explore for shale gas in England need a permit from the Environment Agency. Permits are designed to protect people and the environment from harmful effects caused by releases from permitted sites. One potentially harmful release from exploratory hydraulic fracturing operations is the fugitive emission of methane gas. Emissions of methane are potentially harmful to human health because of their flammability, and because they can contribute to episodes of photochemical air pollution which adversely affect people with respiratory conditions. Moreover, methane is potentially harmful to the environment because it is a powerful greenhouse gas which contributes to climate change.

The Environment Agency may require that operators of exploratory sites quantify methane emissions and, if necessary, monitor the concentrations of ambient methane on their sites and in the surrounding area. Techniques for developing generic emission factors are generally derived from and/or calibrated against measurements carried out in the field. Hence, measurements may be needed to support the development and use of generic methane emission factors, particularly where there are no pre-existing measurement data. This investment in methane emissions measurements can deliver savings, by enabling robust generic techniques to be developed for estimating methane emissions, so avoiding the need for potentially costly bespoke measurements at every site.

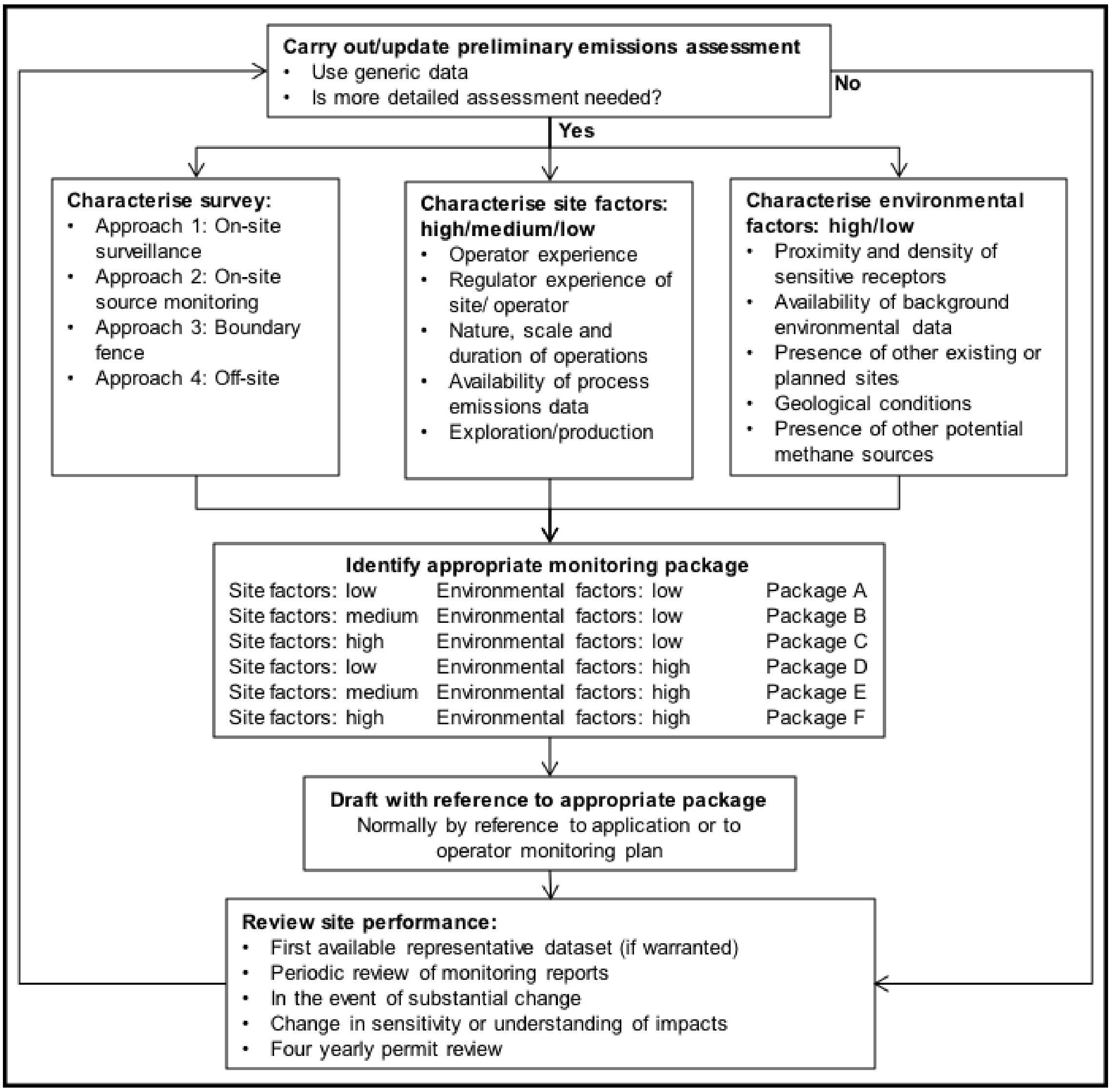
In order to assist in ensuring that methane monitoring is done consistently and effectively, the Environment Agency has commissioned this study to explore how methane monitoring packages could be evolved and to stimulate thinking and discussion within the Environment Agency. The aim is to identify a systematic approach to methane monitoring, so that the monitoring effort is in line with the environmental risks and operator performance at each site. The considerations that are relevant for shale gas operations using hydraulic fracturing are also likely to be relevant for 'unconventional gas' operations in general.

The study covers the following components:

- A description of preliminary steps to understanding if monitoring is needed, and, if so, how the monitoring programme should be designed. A systematic approach is set out which provides for more monitoring effort to be focused where emissions or risks to the environment may be higher, and less where emissions/risks are lower. The systematic approach is summarised in Figure 1.
- A summary of available methane monitoring methods.
- A description of the activities, processes, equipment and sources that may release fugitive methane from unconventional gas facilities. Where possible, an assessment is provided of the likely relative magnitudes of emissions from different activities.
- A description of how the available methane monitoring methods map to possible survey requirements.

- An example application to suggest how a monitoring programme could be implemented for a hypothetical shale gas exploration site.
- A summary of related issues which may arise when carrying out on- and off-site methane monitoring.

Figure 1: Schematic flow diagram of monitoring approach



The method summarised in Figure 1 provides a flexible, structured approach to the assessment and (if necessary) monitoring of methane at unconventional gas installations.

It is recommended that strategic baseline monitoring at a limited number of representative shale gas and/or coalbed methane (CBM) exploration sites in the UK and Europe would be beneficial. It would provide UK-specific information on the scale of methane emissions and associated risks/impacts at such sites, and would assist in putting any such risks into context with other industry sectors.

It is recommended that the Environment Agency and industry bodies should work together to develop methods and data for estimation of emissions from unconventional gas installations.

It is also recommended that the Environment Agency should keep a watching brief on new developments in methane monitoring techniques.

Contents

1. Background

Over the past 15 years, the use of hydraulic fracturing to extract methane from deep shale deposits has become established in the USA, as a method of gas production. These 'shale gas' operations are an important example of how 'unconventional' methods can be used to extract gaseous hydrocarbons from reserves that were inaccessible with previous 'conventional' methods. The relevant 'unconventional ' reserves are defined in the UK context as gas contained in rocks that may or may not contain natural fractures, and which exhibit in situ gas permeability of less than 1 millidarcy (a different definition is used in the USA).

The possibility of similar unconventional gas production is being considered in the UK, where there are also shale deposits. Initial exploration using hydraulic fracturing was carried out in north-west England in 2011 (see Broderick et al. 2011), but this was suspended for a period while the possibility of adverse seismic effects from fracturing was investigated. In December 2012 the government concluded from a study of seismicity that any effects from hydraulic fracturing were minor and manageable, and exploratory activity was therefore permitted to resume.

The Environment Agency is the environmental regulator for shale gas operations in England. From April 2013, Natural Resources Wales (NRW) took over the functions previously carried out by the Environment Agency in relation to unconventional gas in Wales.

Operators who intend to explore for shale gas in England need a permit from the Environment Agency under the Environmental Permitting Regulations (2010). Permits are designed to protect people and the environment from harmful effects caused by releases from permitted sites. One potentially harmful release from exploratory hydraulic fracturing operations is the fugitive emission of methane gas. Emissions of methane are potentially harmful to human health because of their flammability, and because they can contribute to episodes of photochemical air pollution which adversely affect people with respiratory conditions. Moreover, methane is potentially harmful to the environment because it is a powerful greenhouse gas which contributes to climate change.

In order to protect against the potential harmful effects of methane emissions, the Environment Agency needs to ensure that any releases of fugitive methane from exploratory hydraulic fracturing sites are minimised. For this purpose, the Environment Agency may require that operators of exploratory sites quantify methane emissions, and if necessary measure the concentrations of ambient methane on their sites and in surrounding environments.

In order to ensure that such assessment is done consistently and effectively, the Environment Agency has commissioned this study to explore how methane monitoring packages could be evolved systematically, with the aim of stimulating thinking and discussion within the Environment Agency. This study is therefore designed to provide a guide to developing best practice for methane monitoring, and to provide a toolbox from which operators or regulators could identify appropriate methane quantification and monitoring strategies in future. The emphasis is on the use of hydraulic fracturing to explore for shale gas, and so the study title refers to 'shale gas operations'. However, similar considerations for quantifying fugitive methane apply to other 'unconventional' exploratory operations (e.g. for coal-bed methane), so the report is relevant to 'unconventional gas' operations in general. The aim is to identify a systematic approach to methane monitoring which can be used to specify the type and level of fugitive methane monitoring required at individual sites, so that the monitoring effort is in line with the environmental risks and operator performance at each site. The approach has been designed to be readily updatable, as knowledge about hydraulic fracturing facilities increases, and new methane monitoring techniques become available.

The emphasis is on monitoring of fugitive methane from exploratory activities at hydraulic fracturing sites, rather than on monitoring of fugitive methane from any later production activities. Although production activities are not the main focus for this study, it is likely that any information and experience obtained from monitoring at/around exploratory sites will be useful for informing monitoring requirements at the production stage.

This review considers principally exploratory shale gas operations, with reference also to coalbed methane operations. The review draws on a previous study of methane emissions and controls carried out for the Environment Agency (2012a). The previous study included an overview of the use of hydraulic fracturing for shale gas and coalbed methane extraction (see Box 1.1).

Box 1.1: Extract from previous Environment Agency research

1.2.3 Shale gas

Conventional natural gas reservoirs form when gas migrates towards the Earth’s surface from organic-rich source rock and becomes trapped by a layer of impermeable rock. Producers can access the gas by drilling vertical wells into the area where the gas is present, allowing it to flow to the surface. Shale gas resources, however, are contained within relatively impermeable source rock, meaning that the gas does not migrate out of the source rock and into a reservoir where drillers can easily access it. The gas remains in the shale beds, in which it was formed. This means that shale gas reserves differ from conventional gas reserves in terms of two key aspects:

- Shale gas formations are of much lower permeability than conventional gas reservoirs.
- Shale gas formations typically cover a much wider lateral extent than conventional gas reservoirs – for example, the Bowland Shale in northern England is widespread in the Craven Basin, including the Lancaster, Garstang, Settle, Clitheroe and Harrogate districts, south Cumbria and the Isle of Man; also in North Wales, Staffordshire and the East Midlands (BGS 2012).

… Foreseeable shale gas extraction in the UK is likely to be from measures at depths of 1,000–1,900 metres (North UK Petroleum System Bowland Shale) and 3,500–4,700 metres (South UK Petroleum System Liassic Shale) (US EIA 2011).

The low permeability of shale gas plays means that horizontal wells paired with hydraulic fracturing are required in order for natural gas recovery to be viable. The typically extensive area of shale gas formations opens the possibility of extensive development of large gas fields. This is in contrast to conventional gas extraction, which has been localised in nature…

1.2.4 Coalbed methane

Coalbed methane (CBM) is formed through the geological process of coal generation. It is present in varying quantities in all coal and like in shale gas formations it is trapped within the strata – in this case within the coal itself with only 5–9 per cent as free gas. It is exceptionally pure compared to conventional natural gas, with the coalbed gas typically containing 90 per cent methane.

Hydraulic fracturing is sometimes used in CBM deposits to enhance extraction. The process of hydraulic fracturing is as previously described but the effect on the coalbed differs in the extent that the process results in what has been described as rock ‘breakdown’. This is because coal is a very weak material and cannot take much stress without fracturing.

The process can fracture not only the coalbeds but also fracture surrounding strata within or around the targeted zones. The process sometimes can create new fractures but more typically enlarges existing fractures, increasing fracture connections in or around the coalbeds.

2. Introduction to this report

2.1 Objectives

The project is designed to develop methods for evolving generic estimates of methane emissions, together with a set of monitoring regimes to assist in the management of fugitive methane emissions at shale gas sites. It will help the Environment Agency to identify the appropriate monitoring effort required at any given site. To be appropriate, the level will need to be in keeping with (a) the risk potentially posed by the site, (b) the context of the installation itself and (c) any constraints posed by the environmental setting of the site or other relevant factors.

This document does not give a definitive account of methane estimation, monitoring and control techniques, and attention should be paid to other relevant guidance (this is discussed further in Chapter 4). This document explains how monitoring may be used to underpin emissions estimates and controls on fugitive methane emissions.

Although developed for shale gas exploration sites, the estimation techniques, monitoring selection processes and measurement techniques outlined in this report may also be relevant for coalbed methane (CBM) exploration sites. They could also be applicable to unconventional gas sites during the production phase of gas field development, if supported with expert judgement. Indeed, the more comprehensive monitoring packages may be considered more appropriate for larger-scale, longer-duration operations at the exploitation phase.

In order to achieve this overall aim, the report contains the following components:

- A description of the activities, processes, equipment and sources that may release fugitive methane from inside a site's fence line. Where possible, an assessment is provided of the likely relative magnitudes of emissions from different activities (Chapter 3).
- A description of preliminary steps to understanding if monitoring is needed, and if so, how a monitoring programme should be designed. A systematic approach is set out which provides for more monitoring effort to be focused where emissions or risks to the environment may be higher, and less where emissions/risks are lower (Chapter 4).
- A summary of methane monitoring methods available to monitor on-site and off-site activities and sources, including their practicality and costs. This includes a discussion of the methods available to monitor levels and release rates of methane in receiving environments beyond a site's fence line (Chapter 5).
- A description of how the available methane monitoring methods map to possible survey requirements (Chapter 6).
- An example application to suggest how a monitoring programme could be implemented at a hypothetical shale gas exploration site (Chapter 7).
- A summary of related issues which may arise when specifying proportionate regimes of on-site and off-site monitoring (Chapter 8).
- Conclusions and recommendations (Chapter 9).

2.2 Constraints and limitations

This study is designed to provide a robust structure for monitoring of methane at unconventional gas exploration facilities. The study cannot provide complete guidance on appropriate monitoring techniques in all respects for a number of reasons:

- There may not be sufficient scientific evidence to provide a robust analysis of relevant considerations for the study. In this case, it may be appropriate to highlight such aspects as areas for further research.
- Monitoring technologies may not be sufficiently advanced to fulfil all potential study requirements at reasonable cost.
- Developments in monitoring technologies can be expected to bring new monitoring techniques to the marketplace that are not available at the time of writing.
- Resource constraints limit the extent of research that can be undertaken to support this guidance.
- The complexities of individual sites and conditions mean that discretion in the choice of monitoring techniques must lie with the site inspector.

2.3 Regulatory authorities

An introduction to the regulation of shale gas in the UK entitled *What is shale gas*? is provided on the Department of Energy and Climate Change's website (DECC undated). This states:

> From the outset, each application must go through the local planning authority process and before any drilling occurs, an application for authorisation for any discharge must be made to the Environment Agency (EA) or Scottish Environment Protection Agency (SEPA) in Scotland,[1] which will only be granted if the agency is confident that there is no risk to the environment, and in particular to drinking water. As part of this process, operators are required to disclose the content of fracking fluids to the Environment Agency. The Health and Safety Executive [HSE] scrutinises the well design for safety.
>
> The HSE then monitors progress on the well to determine if the operator is conducting operations as planned. The HSE are also notified of any unplanned events. If it is deemed necessary, inspections may be undertaken by HSE to inspect specific well operations on site.

The regulatory process for development of exploration wells is summarised by DECC in the flowchart included here as Figure 2.

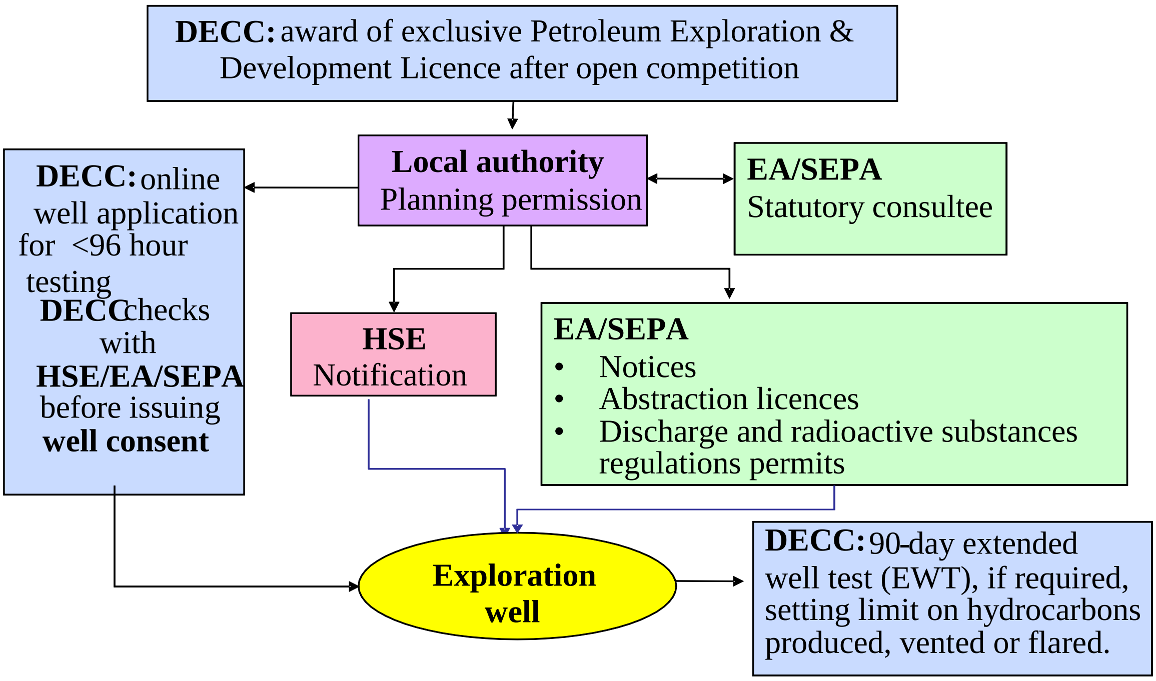
A range of information on the regulatory arrangements for shale gas exploration and development is provided by DECC (2013b) at https://www.gov.uk/oil-and-gas-onshore-exploration-and-production. Of particular interest is the report *About shale gas and hydraulic fracturing (fracking)* (DECC (2013c).

It is important that Environment Agency regulatory officers consult with HSE officers to ensure that monitoring and assessment of methane addresses all potentially relevant

[1] Note: As of 1 April 2013, Natural Resources Wales is the environmental regulator for Wales.

health, safety and environmental issues, and takes advantage of any opportunities for synergistic benefits, but does not result in duplication of effort.

Figure 2: Regulatory process for exploratory well development



3. Sources of methane from unconventional gas operations

This chapter summarises the potential sources of methane arising from unconventional gas exploration. It is also relevant to the consideration of methane arising from production phase activities. The chapter goes on to set out generic estimates, which can be used as the starting point for scoping evaluating methane emissions for such activities. The following chapters explain how these generic estimates should be supplemented by field data appropriate for the UK context.

3.1 On-site activities/sources

The stages in exploratory well-pad development and potential sources of emissions to air are described in a report published by the European Commission (2012a). This analysis drew in particular on publications by the US Environmental Protection Agency (EPA 2011a), the New York State Department of Environment and Conservation (NEC) (2011), and the Tyndall Centre (Broderick et al. 2011) together with other reference data.

These studies found that the largest releases of methane can potentially arise during:

- hydraulic fracturing, principally during the receipt of the flowback water;
- production trials, which can include gas flaring or venting;
- the peak early production years (venting and leaking).

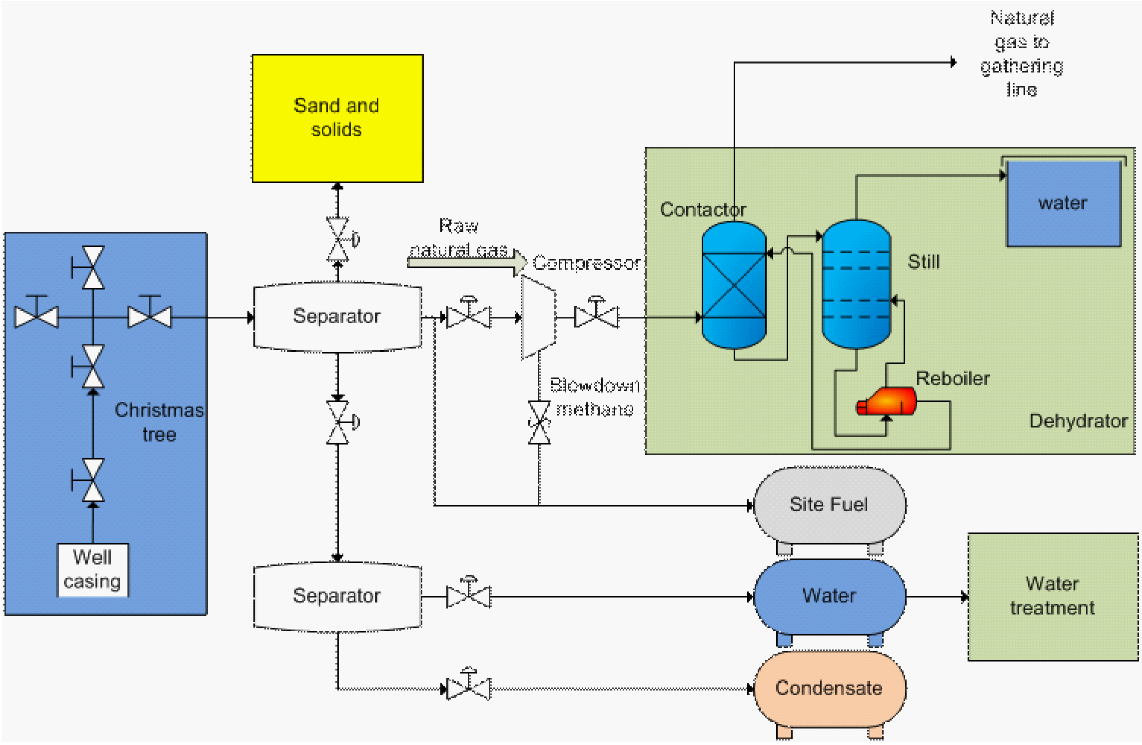
During the drilling, hydraulic fracturing and completing process, there is significantly more infrastructure deployed to the well. This typically involves the use of mobile plant, which is brought to the site, and then removed from the well pad when the relevant stages of the process have been completed. This extra infrastructure may mean that these stages of well development pose higher risks, and consequently methods and protocols have been developed and are available to reduce the risks associated with these activities.

Figure 3 shows a schematic of possible local infrastructure used during completion (mobile or temporary plant) and production (permanent plant).

The simplified schematic of a possible well production facility in Figure 3 shows the natural gas flow from the wellhead through the ‘Christmas tree’ pipework at the wellhead, followed by gas and condensate separation. The gas is fed to a compressor and any local treatment plant (such as dehydration equipment), before the dried raw natural gas is fed into the gathering lines that take the raw natural gas to centralised natural gas processing facilities.

There are risks of significant short-term methane emissions during the period up to the beginning of full production. During the main production phase, the production rate for conventional gas starts at a high level and reduces in rate as a hyperbolic function over time (Ricardo-AEA 2013). Hence, for any individual well, the risk of significant methane emissions reduces over time.

Figure 3: Schematic of local natural gas production facilities



However, a well pad will typically have multiple wells that are drilled, fractured, put into production and refractured over time, and a shale gas field will be served by multiple well pads (Broderick et al. 2011, Ricardo-AEA 2013). Consequently, a long-term development programme will bring new wells into production to maintain gas production rates, and so there may be an ongoing risk of significant methane emissions until the play is no longer economically viable for collection. The lifetime of a well is delimited by the technically available reserves and gas demand. Operational lifetime can be expected to be at least 20 years.

The European Commission study found potential sources of emissions to the air from shale gas exploration facilities as listed in Table 1. Although the focus of the European Commission study was not on climate issues, the study findings give a useful indication of likely sources of methane. These sources may warrant consideration as potential areas for focusing on-site methane monitoring surveys. These sources are also likely to be priorities for emission control measures, and therefore for monitoring to confirm the need for, or the effectiveness of, control measures.

Table 1: Potential sources of methane from shale gas exploration facilities

Source	Short-Term/ Long-Term	Continuous/ Intermittent	Point/Line/ Area/Volume	Height	Controlled/ Uncontrolled
Well pad preparation					
None					
Well drilling					
None					
Hydraulic fracturing					
None					
Completion					
Leakage from pumps	ST	I	P	Typically 0–4 m	C
Leakage from valves	ST	I	P	Typically 0–4 m	C
Leakage from pressure relief valves	ST	I	P	Typically 0–4 m	C
Leakage from flanges	ST	I	P	Typically 0–4 m	C
Leakage from agitators	ST	I	P	Typically 0–4 m	C
Leakage from compressors	ST	I	P	Typically 0–4 m	C
Flowback water storage	ST	I	P/A	Ground level	C/U
Leakage from pipeline	ST	I	P	Typically 0–4 m	C
Release from flaring	ST	I	P	Typically 4–10 m	C
Production					
Release from flaring	LT	C	P	Typically 4–10 m	C
Blowout	ST	I	P	Typically 0–10 m	U
Risk of leakage from well casing via	LT	C	P/A	Ground level	U

Source	Short-Term/ Long-Term	Continuous/ Intermittent	Point/Line/ Area/Volume	Height	Controlled/ Uncontrolled
annular seal					
Leakage from pumps	LT	I	P	Typically 0–4 m	C
Leakage from valves	LT	I	P	Typically 0–4 m	C
Leakage from pressure relief valves	LT	I	P	Typically 0–4 m	C
Leakage from flanges	LT	I	P	Typically 0–4 m	C
Leakage from agitators	LT	I	P	Typically 0–4 m	C
Leakage from compressors	LT	I	P	Typically 0–4 m	C
Flowback water storage	LT	C	P/A	Ground level	C/U
Leakage from pipeline	LT	I	P	Typically 0–4 m	C
Refracturing: as for fracturing	LT				
Post-abandonment					
Risk of leakage from well casing via annular seal	LT	C	P/A	Ground level	U
Risk of leakage from inadequate well bore seal	LT	C	P	Ground level	U

3.2 Generic emission rates

Generic emission rates are generally derived from and/or calibrated against measurements carried out in the field. Hence, the use of generic emission rates does not obviate the need for measurements, particularly in a situation where there is no pre-existing measurement data. When developing measurement data for use in making generic emission estimates, it is important to explain the particular conditions relevant to the measurements, so that the measurement data can be applied appropriately to comparable conditions to obtain valid estimates.

The uncertainty in emissions estimates based on bespoke measurements is due mainly to the uncertainty in the local measurement. Generic estimates should be based on a sufficient sample of similar measured cases – so that the variation between cases is clear. This variation can then be used to attach an estimate of uncertainty to generic emission estimates. As well as measurement uncertainty and variability, uncertainty is also introduced into generic estimates as a result of transferring information between similar, but not identical, sites.

Hence, the development of techniques and tools for making generic methane emissions estimates requires investment in systematic measurements across a range of well-defined cases. This investment can subsequently give a return, if robust generic techniques can be used to estimate methane emissions, avoiding the need to carry out bespoke measurements at every site.

3.3 Overview of sources

Alongside the 2012 European Commission study of environmental risks and regulatory analysis, a second lifecycle assessment study was published by the European Commission DG CLIMA (European Commission 2012b). Based on a review of published literature, this study provided estimated methane emission rates associated with different stages and equipment within the shale gas exploration and production process as listed below.

- Site preparation: No significant methane emissions, other than foregone carbon sequestration due to land-use change.
- Drilling and pumping: No significant methane emissions.
- Transportation of materials: No significant methane emissions.
- Wastewater disposal: No significant methane emissions (methane in wastewater assumed to be lost prior to disposal).
- Well completion: Significant methane emissions during completion (typically over a period of a few days or weeks) with estimates covering the range 10 to 6,800 m^3 per well (0.007 to 5 tonnes/well) – see discussion below. If a well is refractured, methane emissions associated with well completion would recur.
- Production: Significant methane emissions (New York State DEC, 2011).
- Well head: Negligible.
- Compressor: 116 tonnes/well.
- Dehydration equipment: 97 tonnes/well.
- Other equipment: 8 tonnes/well.
- Transportation and distribution: Significant methane emissions, with estimates due to leakage covering the range 0.52 to 3.6% of methane produced. Emissions from compression stations estimated to be approximately 1.4% of methane produced. These emissions would be common to both conventional and unconventional gas distribution networks.
- Well plugging and abandonment: No information on potential leakage, but only likely to be a significant issue if well integrity is compromised.

This indicates that the main contributor to methane emissions associated with gas wells is the production phase. Methane emissions may be associated with compressor plant and dehydration equipment. Well completion emissions are less significant in the overall context of the well lifetime, but are concentrated in a relatively short period of time. This provides the potential for adverse impacts due to methane emissions, but also the opportunity for control during the limited period of well completion. Consequently, methane emissions during well completion are likely to require significant regulatory focus.

3.4 Methane emissions during well completion

Upon completion of hydraulic fracturing a combination of fracturing fluid and water is returned to the surface (flowback). The flowback contains a combination of water, sand, hydrocarbon liquids and natural gas.

Equipment used at conventional gas wells under production conditions, including the piping, separator and storage tanks, are not designed to handle this initial mixture of abrasive fluid. Past practice in the USA has been to vent or flare the natural gas during this step, and direct the wastewater into ponds or tanks (Armendariz 2009). However, new rules introduced by the US EPA will require the use of reduced emissions completion (REC) techniques (also known as green completion) to control methane emissions during completion at the majority of unconventional gas wells (US EPA 2012). REC involves the temporary installation of equipment designed to handle the high initial flow of waste water, and to collect the gas for transmission to the gathering pipeline, or flaring if pipeline connections are not available.

Emissions from the well completion stage are short-term, typically occurring over a period of several days (US EPA 2012). The quantity of methane emitted during completion depends on the level of methane in the water flowback, the quantities of water flowback, the length of the flowback period and the management practices that are applied. The release estimates noted in Table 2 were identified.

Table 2: Methane emissions from flowback water during completion

Source	Estimated natural gas release (thousand m^3 per completion)	Estimated methane release (tonnes per completion)	Basis
US EPA (2012)	20 to 560 (257 average)	137	Data from four industry presentations at a technology transfer workshop (green completions) representing data from over 1,000 well completions, for a range of formation types, with hydraulic fracturing. For each data source, US EPA calculated the average gas release per gas well completion. The four data sources were arithmetically averaged.
Howarth et al. (2011)	140 to 6,800 (2,034 average)	1,085	Data on methane capture for four site (all emissions assumed to be vented in study), and the projected releases for the fifth (and largest) site.
ANGA/ AXPC (URS 2012)	10 to 32 (21 average)	11.2	Calculated gas leakage (using US EPA 2011a calculation methodology) during the completion of 98 (shale gas or tight sand) new gas wells from data provided by five selected companies. Average emissions were calculated by company and by shale gas basin. Only non-REC wells were included in the sample.
Jiang et al. (2011)	39 to 1,508 (603 average)	322	Release per flowback event, based on a modelled release rate and flaring rate.

The use of REC techniques may enable emissions during completion to be reduced by approximately 90%. Additionally, New York State DEC (2011, Appendix 19) estimated that emissions due to incomplete combustion in flares during completion would amount to approximately 12 tons (US) methane per well over a 72 hour period.

3.5 Methane emissions during production

New York State DEC (2011, Appendix 19) provided emission factors for methane emissions during production, as listed in Table 3. These emission factors are from the conventional gas industry.

Table 3: Methane emission factors: production phase

Source	Emission factor	Unit
Fugitive		
Gas well	0.0064	kg/hour per well
Heaters	0.012	kg/hour per heater
Separators	0.00091	kg/hour per separator
Dehydrators	0.019	kg/hour per dehydrator
Meters/piping	0.0077	kg/hour per meter
Large reciprocating compressor	13.3	kg/hour per compressor
Vented		
Pneumatic device vents	0.30	kg/hour per heater
Dehydrator vents	0.20	kg per thousand m^3 throughput
Dehydrator pumps	0.73	kg per thousand m^3 throughput
Compressor blowdown	0.009	kg/hour per compressor
Compressor starts	0.020	kg/hour per compressor

Methane emissions during the production phase were estimated for single-well and four-well pads (see Table 4).

Table 4: Estimated methane emissions during production phase

Source	Single-well pad (tonnes/year)		Four-well pad (tonnes/year)	
	Fugitive	Vented	Fugitive	Vented
First year				
Compressor		111		73
Dehydrator vents	19		53	
Dehydrator pumps	69		191	
Pneumatic device vents	8		5	
Subsequent years				
Compressor		116		116
Dehydrator vents	21		84	
Dehydrator pumps	76		304	
Pneumatic device vents	8		8	

Howarth et al. (2011) compared the fugitive methane emissions during the stages of natural gas production. The study findings are summarised in Table 5.

Table 5: Fugitive methane emissions associated with natural gas production

Source	Fugitive methane emissions as a percentage of well lifetime emissions	
	Conventional	Unconventional
Well completion	0.01%	1.9%
Routine venting and equipment leaks at site	0.3–1.9%	0.3–1.9%
Liquid unloading	0–0.26%	0–0.26%
Gas processing	0–0.19%	0–0.19%
Transport, storage and distribution	1.4–3.6%	1.4–3.6%
Total	1.7–6%	3.6–7.9%

Source: Howarth et al. (2011)

While this work remains controversial and subject to disagreement within the scientific community, it is consistent with the US EPA's view of much higher emissions from well completion for unconventional gas than from conventional gas. A later study by Pétron et al. (2012) provides support for higher emissions from a tight gas field compared to a conventional field. This study suggested that using the established methodology indicated that approximately 2% of methane production was lost to the atmosphere, whereas atmospheric measurements combined with the use of dispersion modelling tools indicated that approximately 4% of methane was lost to the atmosphere during tight gas production.

There are differences between tight gas extraction and shale gas extraction. For example:

- tight gas reservoirs tend to be of higher porosity than shale gas reservoirs;
- shale gas plays tend to cover a more extensive area than tight gas reserves, resulting in different approaches to exploring for tight gas and shale gases.

However, both types of gas reserve typically require horizontal drilling and hydraulic fracturing to enable gas to be extracted, and downstream gas handling and processing systems are similar. Hence, the information obtained by Pétron et al. (2012) for tight gas can be viewed as a reasonable model for shale gas pending the provision of data specific for UK unconventional hydrocarbon operations. It follows that measurement data on methane releases from UK unconventional operations will be useful to clarify whether these operations may release more or less methane per unit of production than the amounts estimated for conventional operations using established methodologies.

4. Systematic approach

Chapter 3 set out the sources of methane which may potentially arise from unconventional gas exploration and production. This chapter sets out considerations for developing a systematic and proportionate approach to methane monitoring, which takes account of site-specific issues and the development of generic methane emissions estimation techniques. After an introduction in Section 4.1, Section 4.2 presents the potential study objectives, and Section 4.3 sets out a proposed hierarchical approach to developing an appropriate methane monitoring programme.

4.1 Introduction

Developing an understanding of fugitive methane from a shale gas exploration site may be needed for a number of reasons. As well as being a potentially significant pollutant in its own right, methane may be an indicator for the presence of other chemicals, and may also indicate problems with the process that need to be addressed. The presence of methane in the air also indicates a loss of potentially valuable product for the operator. As unconventional gas operations are an emerging industry in the UK, there is a strategic need to develop a database of measurements that can be used to develop routine emissions estimates appropriate for UK conditions. This would bring the unconventional gas industry into line with other comparable sectors (e.g. conventional gas production and processing, the landfill sector), where investment in monitoring has been used to develop routine methods of estimating emissions, based on generic factors derived from emission measurements.

Monitoring for methane carries a cost and resource implication, and it is therefore important that, if monitoring for methane is required, it is appropriate to the potential environmental, health and safety risks posed by the presence of methane, while avoiding unnecessary costs due to inappropriate or excessive monitoring. It is also important to ensure that the techniques and study design used are appropriate to the issues of potential concern.

This section therefore sets out a systematic framework for determining an appropriate methane monitoring approach. Complementary frameworks have been developed for related industries and applications, such as the EN 15446:2008 standard for leak detection, and the Energy Institute (2010) protocol for estimating refinery fugitive volatile organic compound (VOC) emissions. Potentially appropriate monitoring approaches are described in this study as 'packages'. A decision must first be taken as to whether methane monitoring is needed. If a field survey is needed, the approach described in this section enables potentially appropriate package(s) to be identified. A monitoring package can be defined in five straightforward steps:

1. Carry out preliminary desk-based evaluation of methane emissions, and decide if methane monitoring is needed.
2. Decide on the objectives of the monitoring survey.
3. Consider whether the site operation should be classified as high, medium or low risk.
4. Consider whether the environmental setting of the site should be classified as high or low risk.
5. Select the appropriate monitoring package from the suite given in Chapters 5 and 6, and adapt for the specific circumstances of the site.

Section 4.3 sets out the factors which need to be considered in determining the operational and environmental risk level for a particular site.

4.2 Potential study objectives

Methane emissions from a shale gas exploratory well typically result from losses of control of gas at some point in the process. Some release of methane from hydrocarbon extraction facilities is inevitable, but any such losses need to be minimised, and it is important to ensure that any such losses do not carry unacceptable environmental, health or safety risks.

There is a wide range of reasons why a regulator or operator may wish to carry out monitoring of methane levels at an unconventional hydrocarbon exploratory well. These reasons may include the following:

1. To determine pre-existing ambient methane concentrations before exploration starts. This is important for both operators and regulators, to enable the results of operational phase monitoring to be properly interpreted and understood. There is a benefit for operators in characterising environmental conditions before starting operations, as this enables any subsequent issues to be dealt with on the basis of a clear understanding of conditions before the activity started.

   Determining baseline conditions is particularly important for exploratory wells in an area where no pre-existing exploration activity has been carried out. Baseline conditions at future wells may be able to draw on the findings of baseline survey work carried out for preceding exploratory development in similar circumstances.

2. To determine ambient methane concentrations during exploration. This may be important to evaluate potential environmental risks and impacts, or to address concerns that may be expressed by regulatory authorities or members of the public.

3. To protect workers against potential safety risks which could occur due to the presence of flammable gases, typically in the immediate vicinity of the wellhead and associated infrastructure. This would normally fall under the occupational safety requirements imposed by the Health and Safety Executive.

4. To establish the pattern of site releases to guide subsequent detailed work. This may comprise a survey to identify the parts of the site from which methane is being emitted, or to rule out certain items of plant and equipment from comprising a significant source of methane. It may also include an analysis of methane levels over time to identify patterns in levels of methane, which may assist in identifying sources of methane emissions.

5. To detect leaks or control malfunctions at particular locations/equipment, usually with a view to identifying plant elements which require maintenance, repair or other intervention to reduce or eliminate methane emissions.

6. To quantify emissions from individual activities or equipment on the site. A study of this nature may be carried out to assist the operator in identifying and implementing measures for reducing methane emissions, and to evaluate the effectiveness of measures and strategies following their implementation. Specifically, exploratory wells are unlikely to have a

connection to the gas collection pipework available. Under these circumstances, it may be necessary to flare methane produced from the exploration well. Methane monitoring may be useful to verify the performance of the flare in providing complete combustion of methane. Monitoring of methane may be appropriate to investigate the influence of factors such as methane production rate and weather conditions on flare performance, if this is a significant issue for an individual site.

7. To assess the overall rate of emissions from the whole site. A study to assess the rate of emissions from a site is typically useful to support an emissions inventory which may be a permit requirement (e.g. in fulfilment of a requirement to report to the Pollution Inventory). In future, the total methane inventory from a site or from the unconventional gas sector may be significant from the perspective of an industry or in the context of national reporting. That is, accurate characterisation of methane emissions from the unconventional gas sector may be important for the overall UK inventory of greenhouse gas emissions. Quantification of site emissions may also be useful to an operator in identifying and prioritising sites which have higher emissions of methane than expected, due to operational, technical or other factors.

8. Emissions inventories are often compiled on the basis of standard data such as emission factors produced by the American Petroleum Institute (API). If an operator has invested in control techniques, a monitoring survey can be a useful way of verifying the benefit of these techniques in reducing the inventory of methane. A monitoring survey can be used to assist in developing emissions estimates if calculation methods are not appropriate for other reasons; for example, it can help where a more robust inventory is needed, or where a facility does not fit the parameters of standard emission factor methods. Also, as part of a wider programme of work, a monitoring survey can contribute to the development of emission estimation methods and databases for an emerging industry.

9. To distinguish site emissions and impacts from those of ‘background’ sources. A study of this nature may be useful in the event of concerns being raised in relation to the potential impact of a particular site. A monitoring survey is likely to be a useful component of developing a robust analysis and response to such concerns – either to show that the site is not responsible for such impacts, or to identify and address the causes of any off-site impacts. In this context it may help to use carbon isotope techniques to distinguish between biogenic methane (e.g. present-day methane from agricultural activities) and thermogenic methane (e.g. fossil methane from exploratory activities).

10. To determine impacts on receiving environments beyond the site. This is a potentially important aspect of permitting, both to establish the impact of a particular facility and also to provide useful data to support potential future assessments of further exploration and production facilities.

11. To determine any residual emissions after exploration is completed. Such emissions could potentially arise from sources such as inadequately sealed wells or pipework. Periodic or continuous monitoring of methane may be appropriate for an extended period of time following site closure.

In the light of this range of reasons for monitoring methane, the uses to which monitoring data are put may include:

1. Tracking improvements in control, or reductions in the standard of control, for example by determining operational methane levels, and comparing to measured baseline levels prior to operations. An analysis of this nature will require careful interpretation in the light of meteorological conditions, and other changes in sources of methane (e.g. due to local waste-related or agricultural activity).

2. Assessing whether emissions are compliant with numerical limits specified in permits. This will normally be achieved by measurement at source.

3. Confirming the need for, and/or the effectiveness of, abatement equipment. The need for abatement plant can be assessed by measurement of methane emissions and evaluation against standards for Best Available Techniques, as set out in relevant regulatory guidance (e.g. BAT reference notes, BREFs), or other authoritative publications (e.g. European standards).

   Effectiveness of abatement plant can often be most readily checked by measurement of methane levels upstream and downstream of the abatement plant. However, it is not always possible to measure either or both of these parameters (e.g. direct measurement of methane levels after flaring is not straightforward). In this situation, alternative approaches may need to be developed.

4. Checking of generic emission estimates by comparison with actual site emissions. This can be useful to enable an operator to demonstrate the benefit of improved controls on a site's methane emissions inventory.

5. Developing improved methods for estimating emissions from unconventional gas exploration activities.

6. Determining the site's contribution to regional photochemical pollution episodes. Again, this can comprise useful supporting information for management of a site under an environmental permit, and for application for/determination of permits for future exploration or production sites.

7. Informing and/or supporting enforcement actions. Where a regulatory officer is concerned about the potential impact of a particular facility on the local or global environment, a monitoring survey can be a very useful means of demonstrating the need for enforcement action, and for verifying the effectiveness of steps taken. Monitoring data are also useful for informing and supporting an operator's response to such regulatory concerns – again, to verify the need or lack of need for intervention, and/or to demonstrate the effectiveness of measures implemented by the operator.

8. Informing policy decisions. Regulatory policy needs to take proper account of a wide range of issues, including evidence for impacts of regulated activities. Evidence from the USA suggests that emissions from intensive shale gas development can have a significant impact on emissions of methane and other greenhouse gases (European Commission 2012a, EPA 2011a, NEC 2011, Broderick et al. 2011). Monitoring during the exploratory phase may provide very useful information to support the development of a balanced regulatory policy in the UK context.

9. Responding to concerns raised by local residents or environment groups. Local residents may be concerned about perceived impacts (e.g. odour or respiratory symptoms) potentially associated with unconventional oil and gas

exploration. Equally, residents may be concerned about the potential for effects on health which are not immediately apparent, or may be concerned about wider environmental impacts such as climate change. In each case, measuring methane can provide useful information to support engagement with local communities over their concerns.

10. Reporting on emissions and site performance, and supporting permit review. This is an important aspect of regulation of any process under environmental permitting. Measurement of methane can provide a useful index of environmental performance, and can be used to support annual reporting under the terms of an environmental permit.

The reason why methane is being monitored will affect the measurement techniques selected, and other features of the study design. The following points need to be considered:

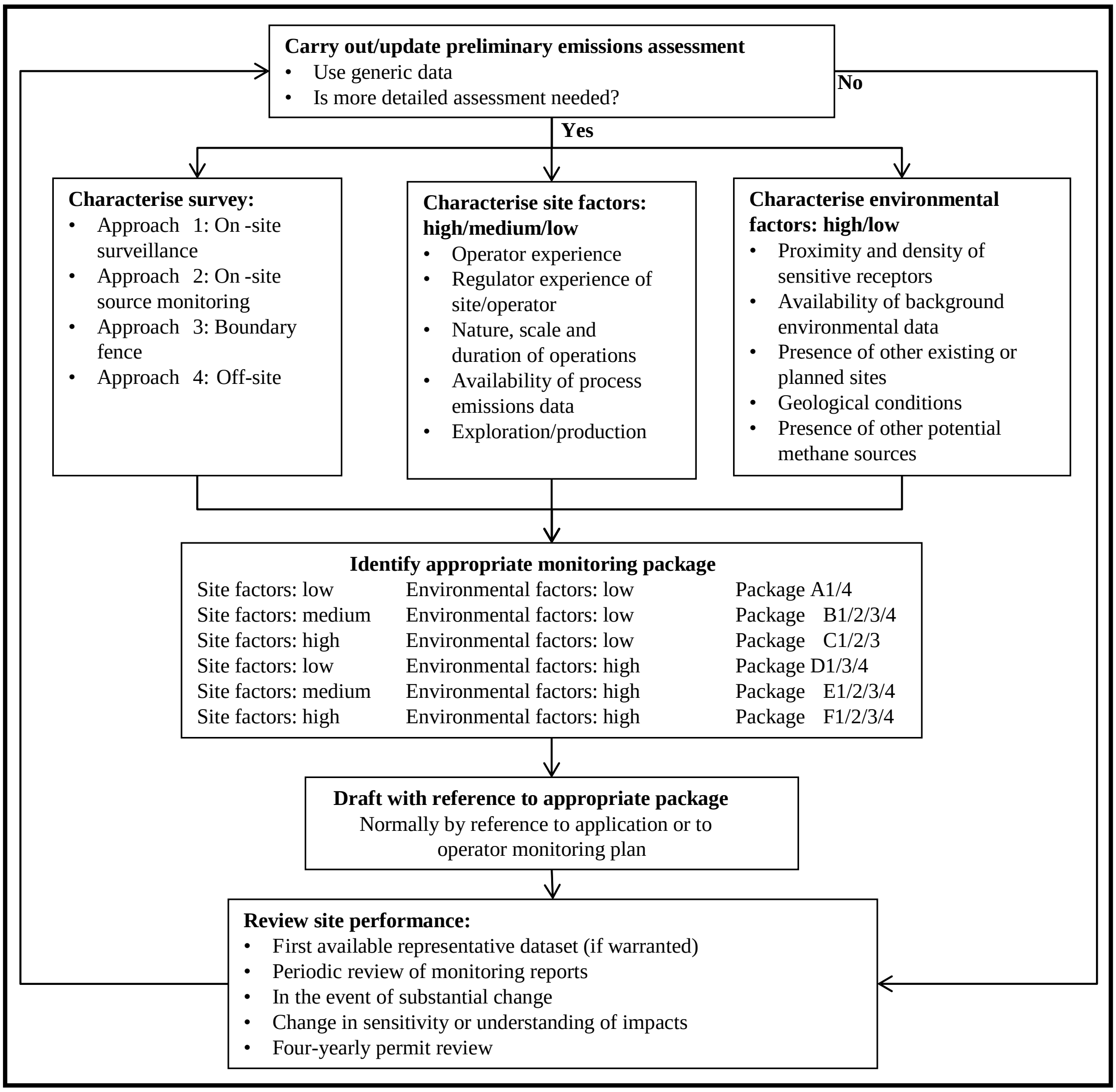
- type of instrument(s) used
- numbers of instruments
- instrument location(s)
- timing of survey
- duration of survey
- other parameters recorded during the survey (e.g. process conditions)
- post-processing and analysis
- reporting

The proposed approach for achieving this in a structured way is set out below in Section 4.3.

4.3 Proposed hierarchical approach

A monitoring plan can be developed using the approach outlined in the following sections, so that the monitoring requirement matches the likely extent of emissions or impacts. The proposed approach is shown schematically in Figure 4.

Figure 4: Schematic flow diagram of monitoring approach



Note: 'Package A1/4' means 'Select one or more of Packages A1 and A4' etc

4.3.1 Identify study objective

Having decided that a field survey is needed, defining the study objectives (see Section 4.2) is the first step in specifying an appropriate monitoring survey design. It is important that the study objectives are carefully considered to identify all potentially relevant uses of the monitoring data. A likely study objective will be to refine the estimated methane emissions from the preliminary evaluation stage.

Other potential study objectives may be linked to the site operational and environmental factors outlined below – for example, a study may be carried out to identify sources of methane at a site with operational difficulties, to investigate methane levels in a local community from where odour complaints have been received, to contribute to the development of an emissions inventory, or to contribute to the development of generic emission factors.

4.3.2 Preliminary evaluation of site emissions

A preliminary evaluation of methane emissions should be carried out. This is likely to constitute a desk study to determine theoretical losses from key process stages (e.g. completion) and equipment (e.g. compressors). This would be derived from generic data for such operating equipment, following established procedures in the conventional hydrocarbons sector. At present, the generic datasets needed to derive such emissions estimates for unconventional gas installations are not available, and it is recognised that industry bodies and regulatory authorities should cooperate to develop such datasets and methodologies.

If the desk study should identify the potential for significant losses of methane from an installation or group of installations, the site operator and/or regulatory authorities can follow the hierarchical approach to design an appropriate field monitoring programme.

In some cases, there may be other indications that methane monitoring should be carried out. Under such circumstances, the operator and/or regulator can follow the hierarchical approach, notwithstanding the favourable results of a preliminary site evaluation.

4.3.3 Classify monitoring study approach

Having defined the study objectives, the approach required in the monitoring plan can be classified as follows:

- Approach 1: On-site surveillance monitoring
- Approach 2: On-site monitoring of specific sources
- Approach 3: Boundary fence monitoring
- Approach 4: Off-site monitoring

A survey may require a combination of two or more of monitoring approaches 1 to 4.

4.3.4 Classify site operational factors

The next step is to understand the relevant operational factors posed by the site in question. A number of factors should be taken into account, where relevant.

1. Operator experience. The installation Operational Risk Appraisal (OPRA) provides useful information on operator experience, as discussed below.

2. Regulator experience of site/operator, drawing on the OPRA where appropriate, as discussed below. The regulatory officers' own experience will be as important as the higher level OPRA summary.

3. Nature, scale and duration of site operations. Useful information to enable site operations to be classified can be obtained from the OPRA, as discussed below. A single exploratory well pad may tend to require a lower level of quantification; multiple exploratory sites may require more detailed study. A single well per well pad would tend to require less analysis; 10 or more wells per pad would tend to indicate more analysis. A site with an estimated 5-year lifetime would tend to require less analysis; a site with an estimated 25-year lifetime would tend to require more analysis. More detailed analysis may be considered appropriate for the production phase of gas field development, when operations can be expected to be larger in scale and longer in duration than during the exploration phase. A site with

ancillary process equipment (e.g. serving a number of well pads) would tend to require more analysis than an exploratory site with gas extraction and flaring alone.

4. Availability of process emissions data. Operators with robust data on emissions from their process (e.g. via a high standard of leak detection and repair (LDAR)) are likely to require lower ongoing monitoring than those with less good data, or who rely on industry standard estimation methods. As the industry develops in England and Wales, new information can be expected to become available, which will lead to a general improvement in understanding of methane emissions from unconventional gas facilities.

The Environment Agency's OPRA system for processes permitted under the Environmental Permitting Regulations (Environment Agency 2012b) addresses the following aspects:

- process complexity
- emissions and inputs
- site location
- operator performance and enforcement history
- record of compliance

Based on an evaluation of the site OPRA assessment and other supporting information, the level of methane monitoring required from the perspective of operational factors should be classified as high, medium or low.

Example: review of operational factors

An application has been received for the first exploratory site in a new shale gas field. The application covers a well pad with up to 10 multi-stage horizontal wells. Forecast flow rate is unknown at present. The operator has no previous record of operations in the UK. It is proposed to use reduced emissions completion techniques to control methane emissions, with flaring of captured methane. The application draws on the operator's experience in the USA and in a small number of exploratory wells drilled elsewhere in the UK, and highlights the uncertainties associated with conditions likely to be encountered in this new development.

The operator has carried out preliminary calculations of emissions using emissions factors developed for the conventional hydrocarbons industry. These calculations do not themselves give cause for concern, but cannot yet be verified as methods and data have not yet been published for estimating methane emissions from unconventional gas facilities in the UK.

Operational risk factors for this development are considered to be medium. This is a balance between the absence of prior problems with this operator due to a lack of experience, and the uncertainty associated with exploration of a new shale gas field. The scale of operations at the proposed well pad is within the expected range of facilities anticipated to be developed in the UK. In view of the uncertainty, it would be appropriate to review operational factors at an early stage.

4.3.5 Classify environmental factors

The next step is to understand the relevant environmental constraints for the site in question. A number of factors need to be taken into account.

1. Proximity and density of sensitive receptors. Locations sensitive to fugitive methane emissions may include residential properties and sensitive habitat sites. Methane itself is non-toxic by inhalation, but the presence of methane may be indicative of the presence of other potentially hazardous substances, such as volatile organic compounds (VOCs). Methane can also give rise to other pollutants, such as low-level atmospheric ozone, or chemical oxygen demand in watercourses. The presence of nearby sensitive receptors would tend to increase the level of detail of an environmental monitoring survey. It may be useful to bear in mind local meteorological conditions (e.g. prevailing wind directions and topographical influences) when considering the presence of potentially sensitive receptors.

2. Availability of background environmental data. For a new development, if adequate baseline measurements of methane have already been carried out, there would be no need for further data to be obtained. Conversely, if there are no adequate baseline measurements, it may be beneficial for such measurements to be required via the permitting process. This would be useful for all parties, by providing a baseline that sets the context for assessing any future measured data.

3. The underlying geology is likely to be a relevant consideration for fugitive methane control, as it is for many other aspects of gas exploration. Geological conditions may affect the composition of gas releases (e.g. whether the presence of methane could be associated with the presence of other potentially hazardous substances). The risk of methane migration from unconventional gas reserves to the surface is typically small, particularly for deeper reserves (European Commission 2012a). However, extraction of coalbed methane (CBM) from near-surface coal seams could pose a greater risk of methane migration to the surface than other gas extraction situations. Shale gas is typically retained in the shale formation as a result of its low permeability rather than necessarily due to the presence of an impermeable cap. Consequently, some shale gas formations may be overlain by permeable formations such as limestone, which could potentially provide a pathway for migration of methane. The presence (known or suspected) of old mine workings or wells in the local area could potentially increase the risk of methane migration.

4. Presence of other existing or planned exploratory sites. An isolated site would have less potential for environmental impacts due to fugitive or vented emissions of methane than a number of sites in close proximity. While this issue is more significant for the development phase of a gas field, nevertheless it may be relevant for exploratory sites.

5. Presence of other potential methane sources (e.g. landfill). Similarly, a site in close proximity to other potential sources of methane such as a landfill or gas pipeline/compressor station may require a more intensive monitoring programme. This may be useful to characterise the baseline in the context of emissions from other local sources, and may also be important in the event of elevated levels of methane being of potential concern in the local area. A methane monitoring study combined with other measurements and assessment tools may be a useful means of distinguishing the contribution of different sources of methane to ambient levels.

Based on this evaluation, the level of methane monitoring required from the perspective of operational factors should be classified as high or low.

Example: review of environmental factors

Example: An application has been received for the first exploratory site in a new shale gas field. The proposed development comprises a well pad located in an agricultural area with cattle farms in close proximity to the exploratory site. An operational landfill site is located 4 km north-east of the site. At present, there is little information on geological conditions, but overlying rock is considered likely to be impermeable, with little evidence of previous drilling in the surrounding area. The application highlights the findings of a pre-existing UK-wide methane monitoring programme, which provides an indicative value for the background methane concentration.

Environmental risk factors for this development are considered to be low. This reflects the low population density in the local area, and the absence of potentially confounding sources of emissions to air. Any off-site monitoring programme should be designed to provide indicative information on background levels to confirm the broad evaluation provided in the permit application. The classification should be reviewed in the light of the findings of any baseline methane monitoring survey.

4.3.6 Select monitoring package

On the basis of the evaluation above, an appropriate methane monitoring package can be identified by following the flowchart in Figure 4. The monitoring 'packages' set out in this section cover a range of scenarios identified as A to F (see Figure 4).

- Scenario A: Site factors: Low — Environmental factors: Low
- Scenario B: Site factors: Medium — Environmental factors: Low
- Scenario C: Site factors: High — Environmental factors: Low
- Scenario D: Site factors: Low — Environmental factors: High
- Scenario E: Site factors: Medium — Environmental factors: High
- Scenario F: Site factors: High — Environmental factors: High

As described in Section 4.3.3, up to four types of monitoring survey could potentially be considered for each of the scenarios A to F:

- Approach 1: On-site surveillance monitoring
- Approach 2: On-site monitoring of specific sources
- Approach 3: Boundary fence monitoring
- Approach 4: Off-site monitoring

Monitoring packages are denoted with a letter and a number – for example, monitoring package B2 would represent on-site monitoring of specific sources for a site classified in scenario B.

These monitoring packages would not necessarily match precedents for monitoring in the conventional oil and gas industry although monitoring package A1 may be consistent with good operational and maintenance practices at comparable installations. Under the systematic approach shown in Figure 4, methane monitoring would only be required if there were a specific reason to consider that a monitoring survey was necessary. The benefit of the systematic approach is that it enables managed consideration of the relevant factors for shale gas facilities to enable a proportionate methane monitoring programme to be developed.

In summary, the relevant monitoring packages are as follows:

- Package A: Minimal intensity monitoring, designed for sites which do not pose a significant risk of adverse impacts due to methane emissions. Confirmatory monitoring carried out where necessary to verify preliminary emissions evaluation.
    - Approach 1: On-site surveillance: May be required
    - Approach 2: On-site source monitoring: Not required
    - Approach 3: Boundary fence monitoring: Not required
    - Approach 4: Off-site monitoring: May be required
- Package B: Monitoring focused on specific on-site issues to rule out as potentially significant sources, or to assist in identification and remediation of methane emissions. Monitoring may be used to assist in quantifying/ characterising emissions and refining preliminary estimates.
    - Approach 1: On-site surveillance: May be required
    - Approach 2: On-site source monitoring: May be required
    - Approach 3: Boundary fence monitoring: May be required
    - Approach 4: Off-site monitoring: May be required
- Package C: Intensive on-site monitoring to address concerns regarding control of methane at sites where there are reasons to believe that emissions may be at a high level. Use of relevant techniques to enable sources to be characterised and where necessary abated.
    - Approach 1: On-site surveillance: May be required
    - Approach 2: On-site source monitoring: May be required
    - Approach 3: Boundary fence monitoring: May be required
    - Approach 4: Off-site monitoring: May be required
- Package D: Monitoring with a focus on characterising methane levels in the local environment in order to establish baseline levels, or to identify other potential contributory sources of methane emissions.
    - Approach 1: On-site surveillance: May be required
    - Approach 2: On-site source monitoring: Not required
    - Approach 3: Boundary fence monitoring: May be required
    - Approach 4: Off-site monitoring: May be required
- Package E: Combination of on-site and environmental monitoring to understand and deal with the site contribution to environmental levels of methane.
    - Approach 1: On-site surveillance: May be required
    - Approach 2: On-site source monitoring: May be required
    - Approach 3: Boundary fence monitoring: May be required
    - Approach 4: Off-site monitoring: May be required

- Package F: Combination of intensive on-site and off-site monitoring to address a situation where there are reasons to believe that an unconventional gas exploration site may be giving rise to an adverse off-site impact, with a view to reducing or eliminating methane sources and improving local environmental conditions.
    - Approach 1: On-site surveillance: May be required
    - Approach 2: On-site source monitoring: May be required
    - Approach 3: Boundary fence monitoring: May be required
    - Approach 4: Off-site monitoring: May be required

Monitoring package A1 would correspond to a basic minimum monitoring requirement that is likely to be carried out by operators as part of normal good working practices. It is likely to comprise checks on plant integrity (e.g. by monitoring pressure drop) together with a LDAR programme appropriate for the nature and scale of the installation.

A description of available methane monitoring systems is provided in Chapter 5. Chapter 6 provides a schedule of monitoring techniques mapped to the six packages. Hypothetical examples of applying such an approach are presented in Chapter 7.

Having identified the most appropriate monitoring package as a starting point, it will then be up to the operator, in discussion with the Environment Agency officer, to adapt the monitoring package for the specific circumstances of the site. Officers will use their discretion to ensure that monitoring requirements are targeted towards issue(s) of potential concern. Using the toolbox of techniques and methods elicited in Chapters 5, and 6, a strategy can be developed to provide an appropriate level of monitoring, having regard to risks and to the costs and benefits of the measurements and analysis.

In many cases, and subject to the discretion of the Environment Agency officer, it may be appropriate to conclude that methane monitoring is not required for one or more of the identified monitoring approaches (on-site surveillance, on-site source monitoring, site boundary monitoring, off-site monitoring). The reasons for reaching this decision should be recorded and subject to review.

Example: identification of monitoring package

For the case study identified above, operational factors were identified as 'medium', and environmental factors as 'low'. This resulted in the identification of monitoring package B, with potential monitoring approaches 1, 2, 3 and 4.

The monitoring survey for this site was defined as follows:

Approach 1: On-site surveillance – Daily site walkover monitoring of methane during hydraulic fracturing/completion using flame ionisation detection (FID) technique or similar. Weekly site walkover monitoring of methane during first month of production using FID technique or similar.

Approach 2: On-site source – Not required, as no evidence of specific sources giving rise to problematic levels of methane.

Approach 3: Boundary fence – Not required, as site methane inventory not needed during exploration phase.

Approach 4: Off site – Walkover survey at nearby sensitive locations using FID technique or similar on three occasions prior to commencement of drilling.

This example is discussed in more detail in Section 7.4.

4.4 Change of classification

Different monitoring regimes are likely to have different frequencies and costs of monitoring, and of data reporting, so that operators who maintain good control of on-site emissions (e.g. lower than typical emissions) could be permitted 'lighter-touch' levels of monitoring. Conversely, where there is poor control, more intensive monitoring may be required until the operator has been able to demonstrate satisfactory control of methane.

As shown in Figure 4, the preliminary emissions evaluation, the requirement for methane monitoring, and the scope of any monitoring survey should be kept under review. This is particularly important during the early stages of gas field development as knowledge is being gained.

The monitoring requirement for an individual site may move up or down in response to changes in knowledge or circumstances. A change in classification may occur for the following reasons:

- Adequate verification or refinement of preliminary emissions estimate has been obtained. Under these circumstances, there is likely to be no further requirement for ongoing monitoring.
- Results of methane monitoring demonstrate that methane levels are within or below normal/expected levels. This may result in a reduced or eliminated monitoring requirement due to reduced site risk.
- Results of methane monitoring demonstrate that methane levels are above normal/expected levels. This may result in an increased monitoring requirement due to increased site risk.
- Interpretation of methane monitoring demonstrates that methane emissions are within or below normal/expected levels by reference to data in Chapter 3 or other appropriate reference. This may result in a reduced or eliminated monitoring requirement due to reduced site risk.
- Interpretation of methane monitoring demonstrates that methane emissions are above normal/expected levels by reference to data in Chapter 3 or other appropriate reference. This may result in an increased monitoring requirement due to increased site risk.
- Occurrence of a problem with methane control on site. This may increase the classification of site risk, and may result in an enhanced requirement for source-specific monitoring of the relevant source(s).
- Solving of a problem with methane control. This may reduce the site risk classification, and may result in reduced or eliminated requirement for source-specific monitoring of the relevant source(s).
- Reduced production rate at the site over time may reduce the site risk, enabling monitoring to be scaled back or ceased.
- Development of other sites in a local area may increase the environmental sensitivity, potentially resulting in an increased methane monitoring requirement.
- Reported odour emissions may increase the classification of site risk and/or environmental sensitivity, potentially resulting in an increased methane monitoring requirement.

5. Methane monitoring methods

The preceding chapters have provided a structure for identifying methane monitoring requirements. This chapter provides a description of the techniques available for measuring methane levels, and some considerations for their application in the field for studies with a range of objectives.

5.1 Introduction

The measurement of methane is guided by a number of factors. The two principal reasons for monitoring methane are:

- Safety: In this case, the near-field concentration is the most relevant. Methane can be explosive if present at concentrations within a defined range. Methane could potentially also act as an asphyxiant if present at elevated levels within a confined space. There is an additional commercial pay-off with near-field assessment in that a loss of methane potentially reduces the overall profitability of the operation. This means that there is also an economic benefit to the operator to monitor and minimise fugitive methane emissions. Safety is an overriding priority. Methane present in air between levels of 5 and 15% and oxygen levels above 13% carries a risk of explosion. The risk is greatest at concentrations of 9.5% at normal conditions (20°C and 1 atmosphere); at these conditions the maximum amount of energy would be realised in any explosion.
- Environmental: The release rate and concentration of methane in the near to medium field is of the most relevance. Methane has a global warming potential (GWP) 25 times greater than carbon dioxide over a 100-year timescale. This factor increases to 72 times that of carbon dioxide over a 20-year timescale (IPCC 2007). Emissions of methane may also contribute to regional air quality issues due to their contribution to the photochemical formation of ozone. There may potentially be impacts resulting from emissions of odours or hazardous air pollutants together with methane.

As discussed in Executive Summary, methane measurements are likely to be useful for developing site-specific emissions estimates. Methane measurements are also used to support the development of techniques for making generic emission estimates. Site measurements are particularly useful in a situation where there is no pre-existing measurement data.

A number of methods can be used to measure methane. The methods used need to be appropriate for the sources encountered during unconventional gas exploration and production, and to have regard to the environment within which the measurements are to be made.

The approach to measuring methane concentration can differ depending on the specific requirement. At the wellhead and local production equipment, identification of leaks and ensuring that the levels of mixtures in enclosed spaces are well below the lower explosive limit (LEL) are the priority.

Hence, for leak detection, it is vital to assess if the released levels are in an explosive range, as well as the location and rate of leak. Total explosive capacity is measured using LEL measurement systems, either in the open air or in a confined space. These measurements are not specific to methane, but typically may include other gaseous hydrocarbons which could potentially form an explosive mixture. In the context of a gas exploration site, methane is likely to constitute the majority of any potentially flammable gas mixture. An LEL meter measures the concentration of flammable gases, rather than measuring an emission rate, on a scale of 0–100% of the LEL of 5% methane volume/volume (v/v). An LEL meter is a safety and reconnaissance tool designed for use where concentrations are relatively high.

For specific production equipment, understanding the rate of leak will form part of the regular measurement regime and part of any equipment performance acceptance test. Further away from the local production equipment, it is important to know that methane is not significantly above the background level at or beyond the plant boundary. In order to make this judgement, it is important that information is available on background levels. This could be determined from a survey carried out prior to the development of the facility, and/or by carrying out upwind and downwind fenceline monitoring.

At the fenceline and in the medium field, measurements can be used for the assessment of methane flux (i.e. the mass release rate over a period of time from a particular installation). As well as concentrations, such measurements must cover wind speed and direction in order to be able to assess fluxes. At larger scales, the overall impact of multiple wells and associated infrastructure on methane concentrations and fluxes can be assessed on a regional basis. Measurements of methane flux may be appropriate to support the development of industry sector, regional and/or national emissions inventories and reports. Methane flux measurements may also be appropriate to investigate local air quality issues such as reported odours for which the specific source is not known. Methane flux measurements can be particularly useful to investigate emissions over a wider area, within which the principal methane sources are not known. Methane flux measurement is discussed in Section 5.5.

The measurement of the absolute level of methane emitted from the well and production equipment, and from other potential fugitive sources, may have some importance. For example, it could be important for assessing wide-area fugitive releases from sources such as shallower coalbed methane plays, which could be emitted via local irregularities and weaknesses in the subsurface structure.

Conventional source emissions monitoring includes the measurement of emissions of methane from controlled vents (stationary sources), but it does not include measurement of fugitive releases. The contribution of fugitive emissions and leaks can be assessed using an enhanced approach to LDAR, using better sensitivity detectors to determine leak rates. This can provide a quality feedback loop into the development of emission factors.

Prior to the commencement of drilling/hydraulic fracturing, it may be useful to characterise the background methane levels if adequate data are not already available. It may be important to distinguish between biogenic methane and thermogenic methane from geological sources. Biogenic methane may have originated from sources such as agriculture and landfill sites. In contrast, thermogenic methane may have come from new 'foreground' sources (e.g. from exploration of the underlying rock). This distinction would require measurement of the isotopic signature of the carbon atoms within the methane.

During drilling and production of gas, the emphasis is likely to be on:

- verification of methane emissions estimates;
- measurement and control of fugitive releases, primarily driven by safety and operational maintenance (LDAR regimes);
- fenceline measurement;
- receptor measurement in the wider community, including incident response.

After well closure, checks and maintenance of the capped well may potentially involve methane monitoring.

Relevant guidance on monitoring methods is provided in the following Environment Agency monitoring technical guidance notes (available via http://webarchive.nationalarchives.gov.uk/20140328084622/http://www.environment-agency.gov.uk/business/regulation/31831.aspx).

- M2 – Monitoring of stack emissions to air (version 9, January 2013)
- M3 – How to assess monitoring arrangements for emissions to air in EPR permit applications
- M8 – Monitoring ambient air (version 2, updated May 2011)
- M16 – Monitoring volatile organic compounds and methane in stack gas emissions (version 4, June 2012)
- M20 – Quality assurance of continuous emissions monitoring systems (updated April 2012)

5.2 Environment Agency environmental monitoring requirements

This section sets out relevant methane monitoring methods, having regard to the above guidance, together with research published by the Environment Agency in August 2012 (Environment Agency 2012a). The relevant sections of the guidance are summarised in Table 6 in Section 5.2.2 below. The measurement methods set out below can be tailored to meet the requirements of Environment Agency guidance. Monitoring requirements will change over time, requiring different approaches, and hence monitoring techniques should be kept under review by regulators and operators.

5.2.1 MCERTs

The Environment Agency established the Monitoring Certification Scheme (MCERTS) to ensure the quality of environmental measurements carried out by operators. This scheme sets performance criteria and standard requirements for equipment, personnel and companies involved in measurement. The scheme currently includes the following:

- Air monitoring:
    - Continuous emission monitoring systems (CEMS)
    - Emissions monitoring from stacks using accredited laboratories and certified staff
    - Monitoring ambient air quality using continuous ambient monitoring systems (CAMS)
    - Emissions sampling/monitoring using isokinetic samplers
    - Portable equipment for emissions monitoring
- Soil monitoring
    - Chemical testing of soil
- Water monitoring
    - Equipment for continuous monitoring of discharge

    - Direct toxicity assessment of effluents and/or receiving waters
    - Portable monitoring equipment
    - Sampling and chemical testing of water
    - Self-monitoring of effluent flow
    - Radioanalytical testing of water
- Environmental data management software

Currently there is no specific category for undertaking measurements associated with the measurement of methane from unconventional sources. However, within the air monitoring category there are sections that provide information that is applicable to this area of measurement:

- **Continuous emission monitoring system** (CEMS) and portable equipment: There are items of equipment that can be used which have had performance assessments and received certification under the scheme. The certifications provide useful information on the capabilities of the analyser. The criteria used to assess the performance are unlikely to be specific to the measurements required for measuring methane from unconventional sources, so care should be taken when reviewing analyser performance data.
- Emissions monitoring from stacks using accredited laboratories and certified staff: This would provide confidence in the data produced because these organisations and personnel are accredited to ISO 17025:2005 under the United Kingdom Accreditation Service (UKAS). The certifications can include accreditation of methods for the measurement of total organic carbon including methane, use of flame ionisation detectors (FIDs), use of absorbent tubes and grab sampling. This accreditation would be against European or international standards as given in Environment Agency monitoring technical guidance note M2.
- CAMS: There is currently not a specific ambient methane analyser certified under the scheme. As there is no legislative requirement to continuously monitor methane it is unlikely that the CAMS scheme will be extended to include ambient methane monitoring techniques.

The approach to monitoring would be to:

- formulate a monitoring plan covering all aspects of the required monitoring;
- use as many components as possible that are certified under the MCERTS (i.e. monitoring contractors, equipment);
- use international, European and national standards to reference and provide methodologies.

This monitoring plan should be agreed with the Environment Agency prior to monitoring taking place. This is the stage when there will be input from a monitoring specialist from within the Environment Agency. If as many aspects as possible of the monitoring under MCERTS are covered, this will aid in the formulation of an agreed monitoring plan.

5.2.2 Environment Agency M Series guidance

The key aspects of the Environment Agency monitoring technical guidance notes with relevance to fugitive methane are summarised in Table 6.

Table 6: Summary of Environment Agency M Series guidance

Document	Relevant aspects of guidance
M2	Monitoring of stack emissions to air • For all extractive methods of gas or particle analysis there is the possibility of leakage of the sample handling line and losses to the walls of the sampling system. Those must be quantified. For manual methods some indications of the possible sources of uncertainty have been in the Environment Agency's Monitoring Technical Guidance notes M2, M3, M8, M16 and M20. For fuller details refer to EN 1911:2010 for manual measurement of hydrogen chloride (HCl), as a typical manual gas sampling example. For instrumental methods, typical sources of uncertainty include lack of fit (linearity), zero drift, span drift, sensitivity to sample volume flow, sensitivity to atmospheric pressure, sensitivity to ambient temperature, sensitivity to electrical voltage, interferences from other gaseous components present in the flue gas, repeatability standard deviation in laboratory at span level, and calibration gas. • The MCERTS performance standards for portable monitoring systems contain the performance requirements for portable emission monitoring systems. These instruments are lightweight, battery powered instruments, which are used to make measurements in a wide variety of applications, such as fugitive emissions and gaseous releases from landfill boreholes. For stack emission monitoring they may be used for indicative purposes. • The sample gas volume depends on the temperature and pressure at the gas meter. These temperature and pressure measurements have associated uncertainty. There may be corrections for water vapour and oxygen level before a result is reported at reference conditions, so the uncertainty of the water vapour and oxygen concentrations must be included.
M3	How to assess monitoring arrangements for emissions to air in EPR permit applications • Continuous monitoring is either required by relevant EC Directives or may be desirable where the levels of emissions are environmentally significant. In these circumstances, continuous monitoring provides improved process control and public reassurance. • Manual sampling and analysis methods may also be required by relevant EC Directives. They are used to meet periodic or intermittent regulatory monitoring requirements and, in some cases, for validation and calibration of CEMS. • If not dictated by mandatory requirements then monitoring standards should be used in the following order of priority as given in the European Commission's IPPC Reference Document on the General Principles of Monitoring (2003):

	Comité Européen de Normalisation (CEN) International Organization for Standardization (ISO) national standards • Alternative methods can be used provided the user can demonstrate equivalence to the reference method by using CEN/TS 14793 – 'Intralaboratory procedure for an alternative method compared to a reference method'. • If the substance cannot be monitored using standards covered by the above, then the following occupational methods may be adapted, following the requirements of BS EN ISO/IEC 17025:2005 so far as possible: Methods for the Determination of Hazardous Substances (MDHS) series published by the Health and Safety Executive (HSE) National Institute for Occupational Safety and Health (NIOSH) Occupational Safety and Health Administration (OSHA) • Operators should be expected to be able to demonstrate compliance with the hierarchy and validate use of non-standard methods, in-house designed/developed methods, standard methods used outside their intended scope and modifications of standard methods to confirm that these methods are fit for purpose. An improvement programme condition may be appropriate in some cases to attain this. • EPR sector-specific and IPPC sector guidance notes include guidance on monitoring requirements and methods based on information derived from the relevant BREFs (BAT reference documents). The notes may include various sector-specific aspects of monitoring. The guidance notes should be adhered to, wherever possible, to ensure consistency across individual sectors. • The positioning of sampling ports for measuring gaseous species is more straightforward than for particulate or aerosol material. It will generally be sufficient to confirm that there is no gaseous stratification in the duct. The Method Implementation Document for BS EN 15259:2007 makes recommendations for the scope of homogeneity tests. • The Operator Monitoring Assessment (OMA) scheme has been extensively revised, extending its application to include the assessment of monitoring arrangements associated with discharges to controlled water (including public sewers and groundwater), as well as air, from EPR installations. • Full details of the four sections in an OMA and the elements that make up each section can be found on at http://webarchive.nationalarchives.gov.uk/20140328084622/http://www.environment-agency.gov.uk/business/regulation/38777.aspx. • Performance standards have been published for monitoring air, land, water and environmental data management software.

	Standards for air include CEMS, CAMS, manual stack emissions monitoring (including personnel), portable emissions monitoring equipment and automatic isokinetic samplers. Details of MCERTS performance standards can be found at https://www.gov.uk/government/collections/monitoring-emissions-to-air-land-and-water-mcerts.
M8	Monitoring ambient air • When deciding whether sampling should be continuous or intermittent, consider the averaging period of the relevant air quality standard or objective with which the data will be compared, whether the impact is acute or chronic and the temporal resolution required (e.g. short peaks averaged over 3 minutes, 1-hour averages, daily averages etc). Short sampling programmes are unlikely to give data representative of general conditions as meteorological conditions and source variations have significant effects on pollutant concentrations. • Also, where short-term peaks are of interest, these may be unusual events occurring for only a few days each year. Hence, short-term monitoring campaigns are of very limited value for characterising air pollution episodes, except for perimeter-fence monitoring of fugitive releases. • Consider both the source and receptor when determining when to sample (e.g. during growing season for pollutant-affected crops, during summer for photochemical episodes, during high wind-speed events for wind-raised dusts). • Fugitive emissions are usually emitted relatively close to the ground level, and are often monitored adjacent to the site boundary. This is known as 'perimeter-fence monitoring'. Open-path monitoring methods are well suited for this because they give a distance-averaged concentration over a long path length such as a boundary. • Sampling from media other than air (e.g. soil, herbage or water sampling) is most commonly carried out when an objective of the study includes the impact of the pollutants on human or animal health, crops, or fauna and flora. In such cases, the pathways by which the pollutants enter the end receptor must be considered and could include ingestion as well as inhalation of the pollutants. • There are numerous factors that have an important bearing on the way in which an ambient air quality survey is carried out. In some cases the survey will form part of a wider monitoring programme that may include measurements of pollutants in water, soil, vegetation or animal tissue. • There are occasions where monitoring appreciably above ground level makes sense. An example of this is where there is need to remove the dominance of ground-level emissions in order to assess the impact of elevated releases. • Pollutant concentrations are significantly affected by temporal variability, such as seasonal variations and diurnal cycles in meteorological conditions and emission patterns;

	weekday/weekend differences; and longer-term variations in, for example, production/manufacturing or fuel usage. Therefore, short-duration sampling programmes are unlikely to give data that cover these different variations, so they may be unrepresentative. • Very often, emissions from sources are diluted and transported within a relatively shallow boundary layer adjacent to the Earth's surface, typically no higher than 100–1,300 m. Within this layer, turbulence, created by the roughness of the terrain, the strength of the wind and by rising parcels of warmer air, causes progressive dilution of the pollutants with cleaner air as the pollutants are transported away from the source by the wind.
M16	Monitoring volatile organic compounds and methane in stack gas emissions • Methane is excluded from the definition of VOCs, but is classed as a greenhouse gas because of its potential contribution to climate change. • There are two published CEN standards for measuring methane. EN ISO 25139:2011 – manual method for methane. EN ISO 25139 is a manual method based on the collection of samples in an inert bag or canister, followed by analysis using gas chromatography in a laboratory. EN ISO 25140:2010 – automated method for methane. EN ISO 25140 is an automated method that uses an FID fitted with a catalytic converter that removes all organic compounds in the sample gas, except methane. • Many simple, unheated, portable FIDs have been designed for applications in health and safety screening, landfill gas monitoring, contaminated land measurements and fugitive emissions monitoring. The simpler FIDs also usually have a wider spectrum of response factors, so their accuracy and precision will never be as great as the highly engineered, complex, heated FIDs. • In order to meet the requirements of the Waste Incineration Directive (WID), Large Combustion Plant Directive LCPD and BS EN 14181:2004, CEMS must meet certain performance requirements evaluated under MCERTS. Under these requirements, once the CEMS have been installed, they must have tests for linearity, checks for zero drift and span drift, and provisions for leak-checking the entire system.
M20	Quality assurance of continuous emissions monitoring systems • Not relevant to this document

5.3 On-site measurement of methane

Equipment for on-site measurements of methane ranges from basic detection devices through to complex systems that are capable of producing quantification data. The following sections provide descriptions of available measurement technologies and of how they can be applied to on-site measurements. These technologies can be divided into two groups: firstly analyser based systems that provided continuous data at the point and time of measurement; and secondly grab samples that are analysed later or away from the point of measurement.

5.3.1 Continuous measurement technologies

Hot bead and catalytic combustion analysers (LEL meters)

Portable combustible gas meters can be calibrated for methane, but are specifically designed to determine the concentration of an explosive gas mixture (not just methane) as a percentage of the lower explosive limit of 5% (50,000 parts per million, ppm).

An ‘LEL’ meter is, however, possibly one of the most important single pieces of equipment for staff locating methane leaks when working around a well or natural gas processing facility – not to pin-point leaks but to alert staff to potentially high levels of methane.

The instrument works by comparing the resistance in a circuit known as a Wheatstone bridge; one of the arms has a catalytic substrate, the other a reference substrate. Combustible gas will ignite on the catalytic substrate, changing the resistance characteristics of the circuit. The change is proportional to the concentration of flammable gases present.

Hand-portable remote infrared – forward-looking infrared and infrared absorption spectroscopy

The basic forward-looking infrared (FLIR) systems have become popular for leak detection within the gas industry, replacing the vapour analysers which were used systematically as part of LDAR to check individual compression fittings, valves and flanges. In practice, FLIR will still be used with other measurement technology to generate required concentration data.

The main benefit of modern FLIR is that a captured, real-time image in the visible and infrared range can be displayed on a screen, allowing the operator to see the actual leaks and methane plumes in situ. This improves the speed of leak detection.

There will be a place for FLIR in assessing fugitive emissions, as it will allow the screening of the production area for further assessment and can also be used for longer-term surveillance. This equipment can be used in the same way as a handheld video camera; it can highlight gas leaks where other methods, such as complex machinery, cannot.

A handheld infrared absorption spectroscopy (IAS) instrument uses a semiconductor laser for methane measurements. The detector measures a fraction of the diffusely reflected beam from its target point. The application has the advantage of working through water and glass, enabling its use during poor weather conditions such as fog and rain. It must be directed at a leak to take the measurement and therefore leaks cannot be found as quickly and easily as with the FLIR technique, though IAS can be used in conjunction with a FLIR system.

It is possible to use airborne FLIR technology to identify sources of methane from larger-scale plant or pipelines. This approach has been used by the Texas Commission on Environmental Quality – a video of a helicopter survey is available (see http://www.yourepeat.com/watch/?v=DT9_kcnuEJw&feature=youtube_gdata).

Flame ionisation detection

The most widely used methane monitoring method is flame ionisation detection (FID). Within the sample chamber, a flame fuelled by hydrocarbon-free air and hydrogen ionises the methane and other VOCs into ionised carbon, changing the current across the chamber to an extent proportional to the VOC concentration.

The hydrogen fuel source is carried in a pressurised gas cylinder, while the hydrocarbon-free air is supplied by either a gas cylinder or a compressor. The FID will require adjustment against a zero gas (nitrogen) and a calibration gas (methane) at an appropriate concentration.

FID detectors respond to all flammable VOCs, not just to methane. The intensity of response varies between chemicals. Instrument manufacturers publish individual VOC response factors for each instrument. In applications where the flammable VOCs may be made up of a wide range of chemicals, this means that FIDs may be less reliable as a quantitative measurement. However, in the case of unconventional gas operations, methane is likely to be the dominant contributor to FID measurements. Additionally, it is possible to determine 'methane only' in higher-end methane/non-methane systems.

This is a standard approach for both methane and non-methane VOC analysis in stack emissions and some comparable landfill gas applications. However, as good as this method is, it comes with inherent dangers in the gas industry. This technique has been used at high-risk sites, where a high accuracy FID is set up for use in a safe zone and bag or canister samples are collected at the measurement point and taken to the instrument for analysis. Alternatively, portable intrinsically safe FIDs are available.

Non-dispersive infrared detection

Non-dispersive infrared (NDIR) absorption spectroscopy uses the principle of infrared (IR) absorption of a target gas. The NDIR analyser will be set up such that the wavelength emitted by the IR source will be the same wavelength absorbed by methane. The attenuated IR at the end of the sample cell is detected by a sensitive photo-receptor. The signal is compared to the IR source in an inert gas such as nitrogen. The attenuation of the IR signal is used to calculate the concentration of methane in the test cell.

Different compounds have unique absorption spectra. However, this measurement principle does suffer from cross-interference with water vapour and carbon dioxide, and so the gas does need to be conditioned before entry to the test cell.

Advanced versions of near IR spectroscopy such as cavity enhanced absorption spectroscopy could also be used, but these are more expensive. These more sensitive systems are more commonly associated with ambient measurements and used in vehicular transects, as discussed in the next section.

Cavity enhanced adsorption spectroscopy

Absorption of electromagnetic energy by gases forms the basis of operation of IR absorption analysers using a light source – typically near-infrared and a photo-detector. In very general terms, the attenuation of the signal of the IR source by absorption by a specific gas is used to determine the concentration of that gas. With traditional IR systems, the concentration is determined from knowledge of the original IR source strength compared with the attenuated signal due to the presence of target gas along the IR beam path.

The technique can be specific as almost all molecules in the gas phase have a unique absorption spectrum in the near-infrared; hence a specific gas can be measured by selecting a specific wavelength for the IR source.

This approach is well-developed for:

- those gases that can be measured over short path lengths (i.e. carbon monoxide and carbon dioxide);
- other advances such as Fourier transform infrared (FTIR) devices that can cover multiple gases.
- Open-path sensors that can integrate a sample over a large distance provide important tools.

The challenge has always been sensitivity and measurement uncertainty, caused by changes in source strength and component tolerance of the system introducing baseline and high-gain drift in the detection.

The cavity enhanced adsorption spectroscopy (CEAS) method is a derivative of tunable diode laser absorption spectroscopy (TDLAS). There are two main commercial forms of this technique:

- 'time'-based cavity ringdown spectroscopy (CRDS);
- 'intensity'-based integrated cavity output spectroscopy (ICOS) (so-called fourth-generation CEAS technology).

A tuneable diode laser is used to introduce a near-infrared beam into an absorption cell in which the laser pulse is reflected between two or more highly reflective mirrors, which creates the 'cavity'. The path length of the light in the cavity is not the distance between the mirrors alone, but this length multiplied by the number of times the light is reflected creating virtual path lengths of tens of kilometres.

The laser system at the heart of modern CEAS systems is based on a room temperature operating quantum cascade laser (QCL). In CRDS, the light from the laser is blocked by design in pulsed laser systems or some form of shuttering mechanism operates in continuous wave laser systems such as an acousto-optic modulator (AOM) or a chopper. When the source of near-infrared energy is interrupted, the IR already in the cavity will bounce off the mirrors but will lose energy exponentially over time, as no mirror can be fully 100% reflective. The time that it takes the initial IR pulse to decay to zero because of these losses is the 'ringdown'. The IR frequency is tuned to match specific absorption bands of the target gas, so when the IR beam in the cavity passes through the target gas, the decay in the IR intensity is accelerated. The difference in time for complete extinction of the IR beam in the cavity between mirror losses alone and combined mirror and target gas absorption losses is directly proportional to the concentration of the target gas.

The differences in the models come down to a choice of narrow or broadband laser, shutter mechanism, modulation systems and number of mirrors (from simple two-mirror to multiple mirror cavities).

In ICOS, determination is by intensity of the laser pulse (like normal TDLAS) and is not time-based as in CRDS. The basic laser and cavity cell approach are similar. The near-infrared laser can also be introduced at an angle, termed off-axis ICOS. These so-called third- (and fourth-) generation CEAS systems can be more sensitive but are very new to the market.

Development of CEAS systems over the last three decades has reduced measurement errors, improved stability and reduced power consumption, so these systems are becoming much more common as field instruments. However, they involve greater capital outlay compared with cheaper alternatives, with prices around £30,000 for a single analyser. The real advantage comes in the post-procurement maintenance and operation costs, which are much lower. With most other instrument types having upwards of 70% of total lifetime costs as post-purchase operating costs, the long-term use of a CEAS system can become attractive.

5.3.2 Grab sampling and measurement

This section discusses devices and methods for taking and analysing samples that are localised in space and time (often referred to as 'grab' samples). Samples taken in this way can be analysed to enable determination of the detailed hydrocarbon speciation, as well as measurement of methane concentration. Some of the analytical detection methods described as continuous are applicable for analysing samples undertaken using this approach.

Sampling method

US EPA Compendium Methods TO-14A and TO-15 (see http://www.epa.gov/ttnamti1/airtox.html) are the primary methods for air sampling to determine total VOCs and VOC speciation. These methods are deployed in current US EPA sponsored studies into fugitive releases from shale gas completion and production. The methods take a gas sample into a stainless steel sampling canister (Summa canister). The sample is kept stable in the steel vessel. When ready, the gas captured in the canister can be analysed using gas chromatography to separate the constituted components for quantification using mass spectrometry.

Advanced spectrographic pattern recognition software can be used with this assessment (as developed by AEA and currently being used by the University of Wyoming in ongoing ambient measurements in locations affected by unconventional gas extraction).

This method does not provide real-time concentration profiles or provide information relating to where a leak is, but can be used to gather many samples from a large area for fugitive assessment.

This principle of collecting samples for later assessment can allow speciation of hydrocarbons. This approach was used in conjunction with other methods by Pétron et al. (2012) in carrying out a pilot study to characterise methane emissions from the Colorado Front Range, an area of some 20,000 wells north-east of Denver, Colorado.

Canister sampling (or sampling into Tedlar® bags) produces short-time resolved samples, over a period of typically 5 to 15 minutes. The location, time, duration and local meteorological conditions (if possible) need to be recorded as part of the study. The number of samples and their location depend on the study objectives, taking into account aspects such as:

- study area;
- number and complexity of potential sources;
- objective in terms of measurement of methane and/or other VOCs;

- extent to which source apportionment is required, or whether the objective is to estimate an overall emission flux;
- extent of meteorological measurements;
- whether the measurement survey is supplemented by dispersion modelling analysis;
- level of quality required in the measurement and analysis.

Determination of methane concentration

Determination of the concentration of methane is typically performed by CEAS. The aim in many modern studies is to speciate the VOCs to look for ratio fingerprints to facilitate source apportionment. The metrics of interest for studies of this nature are ratios of the concentration of the alkanes to the concentration of the alkanes in a representative background, the data being expressed as the median mixing ratio. These measurements, coupled with appropriate meteorological data, can show from which direction the strongest mixing ratio emanates. Larger-scale studies with sampling from multiple locations under different wind directions could be used to triangulate such information, with the aim of identifying individual sources.

5.3.3 Leak detection and repair

All the component parts at a wellhead should have been catalogued and brought into a LDAR regime. There are environmental, safety and commercial reasons for minimising leaks at gas production facilities. The first stage is to identify the leaks. The oil and gas processing industry has a systematic approach to controlled and fugitive natural gas emissions based on risk and cost–benefit analysis (Energy Institute 2010).

For natural gas leaks, a common approach is to first identify the major processes at the site including compressors, separators, storage tanks, all pipe connections, valves, flanges, vents and open-ended pipes. In the process known as LDAR, the risks of emissions and leaks are calculated and each connection is assessed so that a complete catalogue of potential leakage points can be made and issues dealt with directly. LDAR is a reconnaissance process, and an operator would need to go beyond the requirements of LDAR in some regards in order to develop an emissions inventory.

Historically, the LDAR process was completed using calibrated handheld devices, such as intrinsically safe FIDs or catalytic combustion detectors, with a small probe to scan along all the identified weak points. Specific detection protocols were developed but generally followed the principle that a concentration at the component has to be above a leak definition criterion, typically 10–100% of the LEL. The local background level of methane also needs to be considered.

On detection of a leak, the regime for repair when above the ‘definition’ level can vary between 48 hours and 15 weeks, depending on local regulations. This repair schedule can be longer if significant plant shutdown is needed to enable the repairs to be carried out safely. In these cases, it may be judged most practicable to postpone the repair until the next planned shutdown.

This does not mean that leaks causing local methane concentrations below the definition criterion will not be addressed. In addition to the concentration, knowledge of the rate of leak is important – whether calculated from equipment emission factors or measured directly. For low-level leaks, if the rate of methane release results in a monetised loss of methane greater than the cost of repair, then the repair would be carried out.

The LDAR process has been improved with the use of new technology, specifically the use of IR thermal imaging. The standard IR technology is adjusted so that the detector is tuned to a specific wavelength at which a methane leak will show up as a visible image. This advance has improved the speed of the LDAR process and, depending on the system, whole process areas can be scanned.

Following the closure of the site, the well is capped, though this can be limited to the isolation of the 'Christmas tree' pipework if the closure is temporary. Leaks can develop over time, so a closed well will have an ongoing requirement for periodic monitoring.

As well as leakages, there are other controlled releases of methane such as those from vents, safety release valves and equipment blowdowns. Compressors are reciprocating engines that drive a piston to compress the natural gas for production and transportation requirements. In normal operation, there are known leak issues from vents and from the piston rods. When not in operation, it had been usual practice to depressurise the isolated system (blowdown), resulting in a potentially significant loss of natural gas. Additionally, the isolation valves from the pressurised gas pipeline can leak into the compressor and out through the blowdown vent to provide a constant emission. These emissions can be mitigated by measures ranging from simply avoiding blowdown and locking off the piston rod, to recovering the gas from the blowdown vent (such as feeding into a lower pressure site gas fuel supply). Compressor blowdown and rod packing technology are important control features.

5.3.4 Leak rate determination

Determination of the leak rate is necessary to generate evidence for the need to repair minor leaks and to compile greenhouse gas emissions estimates.

From the methane concentration, resources such as stratified screening value tables can be used to estimate the leak rate from the concentration and component type. Determination of leakage rates in this way can carry large uncertainties because of the application of data from previous measurements to a new situation. The emission factors are largely historical and seldom updated, and the original measurements would themselves have been subject to some uncertainty. Emission factors are provided by:

- Canadian Gas Association emission inventory (CGA 1994)
- Gas Research Institute/US EPA natural gas industry study (GRI and US EPA 1996)

The use of emission factors is the basis for companies to estimate their global methane emissions for LDAR results. The data are based on a three-tier system:

- Tier I is based on pipeline length. It is a very approximate method that does not take account of the presence of specific plant and equipment.
- Tier II is based on the number of major process/stations.
- Tier III is based on individual component counts/events.

Direct measurement is also used, typically in relation to the high-risk components such as compressors. The potential source of leak or whole component is sealed in an enclosure ('bagged' up). A known flow of inert gas is introduced to the gas and the flow of total gas (inert plus leak) is measured at an outlet; knowing the concentration of methane, the mass emission rate of methane can be calculated. This emission rate and the recorded leak concentration at the component can be used to derive an emission factor.

An alternative to bagging is to use a system developed by the Gas Research Institute that samples the leak at a high rate, creating a fast-moving field of air with a known flow rate around the immediate source of the leak (GRI and US EPA 1996). The sample flow rate and methane concentration are measured and the mass emission rate of methane can then be calculated. This has the major advantage of being portable and much easier to use than the bagging method.

5.3.5 Monitoring of gas flaring

There are a number of approaches to flaring, ranging from enclosed flares to fire pits. The Environment Agency considers enclosed flares to represent Best Available Technology (BAT). In the USA, the flares associated with hydrocarbon exploration and extraction tend to be open flares (rather than enclosed flares). There are significant difficulties in obtaining a reliable quantification of emissions from open flares for a number of reasons. Primarily, the physical arrangement of the flare causes the main issue; because there is no containment of the flame it does not present a physical point of measurement. An open flame results in varying combustion and significant movement in the flame. The varying combustion can be caused by weather conditions, gas flow rate and composition, which make obtaining reliable concentration data a major challenge.

There have been a number of studies using remote monitoring techniques such as differential optical absorption spectroscopy (DOAS) and light detection and ranging (LIDAR) to investigate the emissions from open flares (see, for example, Renata et al. 2011). LIDAR can be used to generate a three-dimensional concentration map of the plume.

The UNFCCC provides a tool to determine emissions from flaring gas containing methane (UNFCCC undated). The tool provides procedures to determine the projected emissions from flaring of the residual gas stream in a year and the flare efficiency based on measurements or default values. The tool is applicable to both enclosed and open flares. It uses parameters such as the:

- volumetric fraction of methane present in the gas;
- volumetric flow rate of the gas stream;
- volumetric fraction of oxygen in exhaust;
- concentration of methane in the exhaust applicable to enclosed flares;
- temperature in the exhaust gas of enclosed flares.

Flare efficiency of open flares cannot be measured in a reliable manner so the tool uses a default value of 50% assuming that the flare is operational (demonstrated through a flame detection system reporting electronically on continuous basis). If the flare is not operational the default value to be adopted for flare efficiency is 0%.

These parameters are then used to determine the overall methane emission from the flare for the period.

5.4 Site boundary and off-site measurements

There are a number of techniques that can be used to monitor off site. These are described in the following sections.

5.4.1 Path-integrated optical remote sensing

This technique can be used to assess fugitive emissions from associated open sources or whole-site fenceline assessment (such as in refineries). The following four main technologies are used:

- Open-path Fourier transform infrared (OP-FTIR) (>100 m path length).
- Ultraviolet (UV) differential optical absorption spectroscopy (UV-DOAS) (>250 m path length).
- Tunable diode laser absorption spectroscopy (TDLAS) (>250 m path length).
- Path-integrated differential absorption light (PI-DIAL) detection and ranging (1,000 m path length).

These technologies measure a path-integrated concentration and can be used for either hotspot identification or flux measurements (see Section 5.5).

Background levels of methane in the atmosphere away from significant sources are approximately 1.8 ppm. Any measurement survey needs to measure perturbations away from this baseline level. The presence of a detectable background level of methane may also have implications for calibration and use of methane monitoring techniques in the field.

The common principle is to measure the absorption spectra of the target gases. With the IR and UV systems, these require a transmitter and receiver along the path of the beam. These can either be discrete (i.e. a fixed transmitter sending a beam to a receiver) or a combined unit in which the beam is reflected from a mirror. The IR and UV systems can also be used in a passive mode; this is more common for FTIR-based systems in which the Sun is used as a broadband source in a process called solar occultation.

These systems are complex and expensive compared with the other techniques discussed. Some data provided by the US EPA Environmental Technology Verification Program and other sources are given in Table 7. The application of advanced plume mapping methodology may enable large areas (such as a region with many wells or associated processes) to be assessed in order to derive an estimation of the overall emission rate to reconcile any bottom-up greenhouse gas inventory.

Short-term monitoring campaigns (such as the open-path methods and discrete sampling) can be used to provide short-term concentration profiles. These systems can also be used for long-term measurement, although this is often achieved by the use of continuous discrete sampling systems such as FID or a CEAS-based system.

Table 7: Summary of open-path systems

Item	UV-DOAS	OP-TDLAS	OP-FTIR	LIDAR/DIAL
Price	£39,000–250,000	~£50,000	£50,000–80,000	Bespoke systems in the region of £500,000+
Minimum detection limit	Benzene: 0.4–1.5 ppb	0.29–0.56 ppm Can drop to 2 ppm at distances	Ethylene: 0.32 ppm	76 ppb at 1,000 m
Linearity	Slope: 0.95 R^2 = 99%	Slope: 0.95 R^2 = 99%	Slope: 0.99 R^2 = 99%	

Item	UV-DOAS	OP-TDLAS	OP-FTIR	LIDAR/DIAL
Accuracy	2.1–14%	5.2–11%	1.6–7%	
Precision (relative SD)	0.57% at 100 ppb	1.24% at 500 ppm and 220 m	0.53% at 50 ppm and 200 m	
Interference	None seen (tested for O_2 and O_3)	None seen (tested for CO_2 and H_2O)	None seen (tested for CO_2 and H_2O)	
Field use	Range up to 500 m	Compact, quick response, high resolution	Rugged Range: 400–500 m Needs to intercept a large proportion of the plume	Portable (lorry) Range up to 3,000 m Capable of spatial resolution
Target gas	Not specific – methane is an added extra to the standard suite	Single wavelength – target gas specific, needs good weather	Not specific – relies on spectral library	Not specific (multiple wavelengths) Not real-time Weather dependent

Notes:

UV-DOAS = ultraviolet differential optical absorption spectroscopy

OP-TDLAS = open-path tunable diode laser absorption spectroscopy

OP-FTIR = open-path Fourier transform infrared

LIDAR/DIAL = light detection and ranging using differential absorption

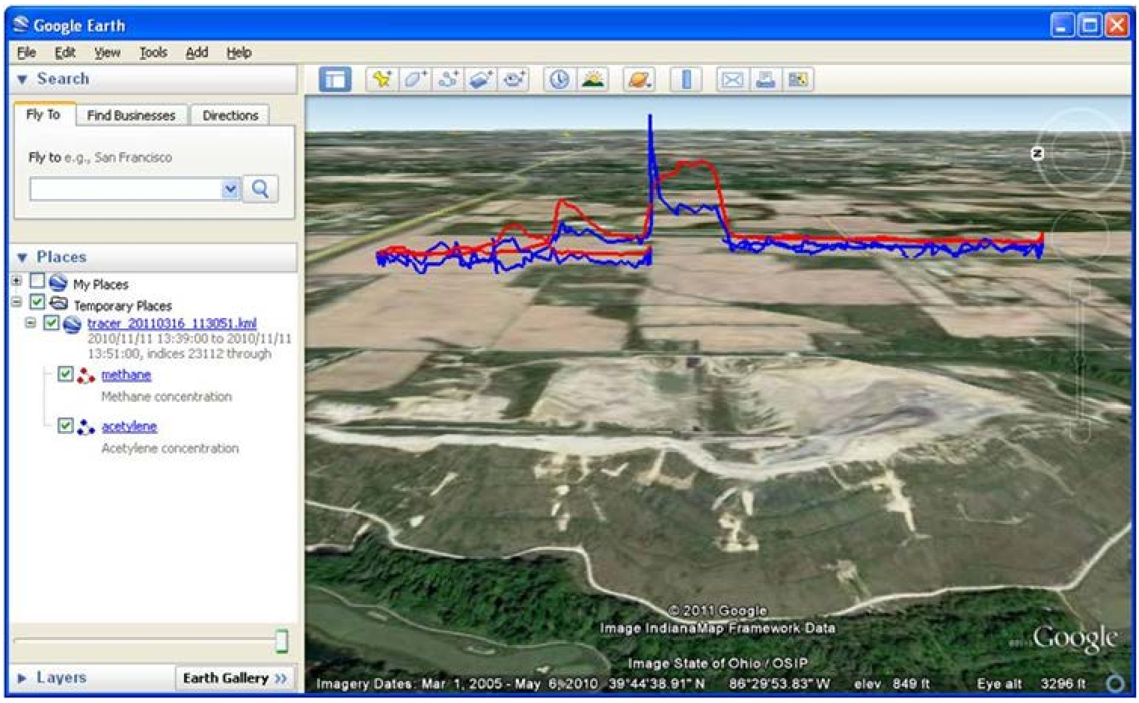
5.4.2 Mobile CEAS-based systems used with tracer gas correlation

These systems are used in laboratories and in the field for accurate ambient concentration measurement. Field applications are for wide-area fugitive methane releases. Examples have been used recently in the development of a fugitive methane emissions protocol for landfill and so could be applied to gas pipeline leak assessment or fugitive release in coalbed methane play development.

Depending on the system, they can be linked to meteorological measurements and GPS systems. Demonstration projects have been completed using vehicle-mounted CRDS systems to develop large-scale methane release mapping and the applicability of these protocols to unconventional gas production is currently being explored.

Figure 5 shows a typical modern CRDS instrument output from a vehicle-mounted unit. The data are exported in a format directly compatible with Google Earth. The speed of response of CEAS-based systems is a critical factor because transect data need to be collected rapidly. The figure shows the transect concentration profile for the target gas (methane) and the tracer gas (acetylene). Concurrent meteorological data are essential for interpreting transect data.

Figure 5: Methane transect from vehicle-mounted CRDS with GPS



5.4.3 Array monitoring techniques

Array monitoring systems involve positioning of a number of detection systems around a specific location (usually a potential source of pollution) and linking each of the detectors to a central logging/data collection system.

Field or array measurements can be used with statistical analysis and computational modelling to find ‘hotspots’ in the methane concentration field, and hence aid the identification of significant sources over a large area. Again, complementary meteorological data are needed to enable array monitoring data to be interpreted. The modelling can include ‘inverse-dispersion modelling’ to determine localised emission rates.

Some detectors which could be used in this way are used for other modes of monitoring and described in previous sections. For example, FID instrumentation may be an appropriate technique for this type of measurement, and has been successfully deployed at landfill sites in the UK.

Laser diode arrays can be used for multiple pollutant monitoring. This system uses tuneable diode lasers. These devices can be tuned specifically to provide measurement of methane. When a number of these devices are combined, the emissions from an area can also be monitored

There are also technologies under development using novel carbon nanotubes (CNT) on alumina substrates. A miniaturised CNT-based gas sensor array was developed for monitoring landfill gas. Using various specifications of CNT, an array capable of sampling and determining the chemical composition of multicomponent gas mixtures was developed. The array sensor is capable of measuring methane, carbon dioxide, hydrogen, ammonia, carbon monoxide and nitrogen dioxide. The sensing properties of the metal-decorated and vertically aligned CNT sensor arrays may enable methane levels to be measured with low power consumption and moderate sensor temperature and as such could provide a useful technology to monitor around unconventional gas production sites.

5.4.4 Reverse modelling techniques

This method can use a single downwind ambient measurement point to measure methane and meteorological conditions. An atmospheric dispersion model can then be used to calculate the emission rate indirectly. Measurement can be a point source instrument (such as a CEAS technology) or an open-path method.

One method is called backward Lagrangian stochastic inverse-dispersion modelling and has been fully validated using tracer gas and multiple path measurements (Flesch et al. 2004). A suspected source emits an assumed emission rate; the unknown factor is the rate Q (kg/m^2/s). A time-resolved concentration C is measured at a defined location M (in the downwind plume); the background concentration (i.e. upwind) also needs to be measured (C_b). The backward Lagrangian stochastic model will calculate the ratio of concentration to the emission rate $(C/Q)_{sim}$ and the emission rate is estimated from:

$$Q = \frac{C - C_b}{(C/Q)_{sim}}$$

This method requires a single measurement point downwind of the source. The important factor is the calculation of the concentration to emission rate ratio. The model predicts the path of a fluid from a defined location backwards in time, thus predicting the source. The strength of the model is that it uses multiple possible paths which the methane ‘particle’ may have taken (Lagrangian) and will emulate the turbulent, random motion of each ‘particle’ (stochastic).

The inputs to the model for area sources are the wind data from the meteorological measurements, the surface roughness (Z_0) and the Monin–Obukov stability of the atmosphere near to the ground (L). The ‘particle’ trajectories are calculated to ‘touchdown’ points and vertical velocities, where the ‘particles’ will have impacted the ground. Thousands of upwind trajectories will be calculated and those that have impacted within the boundary of the source are used to calculate the concentration to emission rate ratio.

A similar approach could be taken with the US EPA Community Multiscale Air Quality adjoint (CMAQ_ADJ) model but would need further use in this version of the CMAQ toolkit to test its applicability (see further discussion in Section 5.5.1 below).

5.4.5 Source attribution: chemical and isotopic techniques

When carrying out a monitoring survey, it may be important to differentiate between different sources of methane. Particular sources of methane may be identified by measuring and analysing the mixture of chemical species present (i.e. by chemical speciation) or the different carbon isotopes present (i.e. by carbon isotope speciation).

Chemical speciation

A specific profile based on the ratios of methane to the heavier hydrocarbons from the well can act as a signature. Knowledge of these ratios for a number of wells can aid in source apportionment. This analysis relies on a reliable understanding of the trace hydrocarbons present in emissions from unconventional gas processes. This information can be gained from source measurements and/or from an analysis of environmental measurements (R. Field, personal communication, 2011).

If the profile of methane and other alkanes is known (C_2–C_5), subsequent discrete air measurements with alkane speciation can be used to compare the emissions profile to the ambient measurement. The measurement can be extended to other trace species in the emission. Emissions of raw natural gas from venting have a different profile to flash emissions, with the flash emissions having a higher C_{2+} component. This alkane ratio approach has been used to corroborate emissions inventories, but involves very detailed measurement work that uses ratio profiling alongside additional measurements (Pétron et al. 2012).

The Denver hydrocarbon emission characterisation reported by Pétron et al. (2012) used a mixture of fixed and mobile measurements. The fixed measurements were carried out using the existing NOAA tall tower network of atmospheric dynamics measurement systems, which included measurements of:

- continuous carbon dioxide (CO_2) and carbon monoxide (CO) instruments measuring samples taken at 22, 100 and 300 m above ground level;
- continuous ozone analysers – one at ground level and one at 300 m above ground level;
- discrete sample collection using the daily midday sample at 300 m. The samples were analysed for methane, carbon dioxide, propane (C_3H_8), *n*-butane (n-C_4H_{10}), isopentane (i-C_5H_{12}), *n*-pentane (n-C_5H_{12}), acetylene (C_2H_2), benzene (C_6H_6), chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs). Wind speed and direction were also recorded.

The mobile measurements made by Pétron et al. (2012) were two-phase. Firstly, a series of collection flasks was used to collect discrete samples at pre-determined locations. Secondly, a further vehicle-mounted wavelength scanned Cavity Ring-Down Spectroscopy System (CRDS) was used to measure carbon dioxide and methane; an infrared gas filter correlation analyser was used for carbon monoxide; a UV absorption analyser was used for ozone; and a global positioning system was used to undertake 6-hour transects. During transects where high methane levels were detected, additional discrete flask measurements were made.

The additional data collected enabled the team to analyse the relative median mixing ratios of the different components from known air mass sources (tall tower sampling) and from discrete sources using the mobile approach. The measurement exercise was dependent on prior knowledge of emission profiles, not just from the wells but from other sources of methane and alkanes. The study showed the value of using pre-existing measurement networks with multiple species being measured, and enhancing this with localised mobile measurement systems.

Carbon isotope speciation

The methane contained in coalbed seams and in shale is predominantly derived from thermogenic sources. Ancient organic matter (carbon, hydrogen and oxygen) in deposited sediments degenerates over time under high temperature and pressure conditions into hydrocarbons. Coal and oil can thermally decompose into natural gas.

The gas will rise through any permeable substrate until blocked by an impermeable layer, forming a reservoir. However, microbial methane can also be found alongside thermogenic methane in coalbed plays. Microbial methane comes from the reduction of carbon dioxide in water or the fermentation of acetate in freshwater.

A measurement of methane by itself will not differentiate between recent methane and fossil methane. A commonly applied test is to determine the amount of radioactive carbon-14 (^{14}C). When organic material is part of a living organism, it incorporates the available carbon in the atmosphere in the form of carbon dioxide. Carbon is mostly present as the stable isotope carbon-12, but also includes the radioactive carbon-14, formed in the upper atmosphere at a near constant rate from the neutron activation of nitrogen from the impact of high-energy cosmic radiation on the Earth's atmosphere. In this process the nitrogen loses a proton and gains a neutron to result in a heavy isotope of carbon.

Ancient thermogenic methane is also originally derived from living matter. This process can take millions of years and the methane can remain trapped in a subterranean reservoir for tens to hundreds of millions of years. A large proportion of the available carbon-14 locked into this fossil methane will have decayed according to the radioactive half-life of carbon-14 of 5,730 years. The carbon-14 will undergo radioactive beta decay, where a neutron in the unstable carbon isotope will decay into a proton and an electron and electron anti-neutrino, resulting in a stable nitrogen-14 isotope.

This is the basis for radio-carbon dating. The techniques developed for this determination can be used to speciate the carbon isotopes in the fugitive methane to differentiate methane from recent or ancient sources. Carbon isotope signatures of methane in ambient air can be measured using a methane carbon isotope analyser. Such measurements can be used to distinguish between thermogenic methane from geological formations such as shale or conventional gas reserves, and biogenic methane from sources such as agriculture or landfills.

5.5 Flux measurements

5.5.1 Overview

The term 'methane flux' in this context means the overall flow of methane from an unconventional gas facility, expressed as mass flow per unit time. It may also refer to the flow of methane through a conceptual plane perpendicular to the wind direction located downwind of the facility. In this case, the flux of methane is expressed as mass flow per unit area per unit time. In this case, flux is often calculated by multiplying a concentration by an air flow velocity.

A number of approaches are available for estimating methane fluxes:

- Emission factors. Using published emission factors and knowledge of the type and number of components in the production process, a budget of methane releases can be estimated. Such an approach can be augmented using knowledge from site-specific LDAR surveys.
- Flux emission measurement. This involves using either point source, transect or open-path or optical remote technology (or a combination) coupled with quality meteorological data with statistical assessment and modelling.
- Radial plume mapping (e.g. according to US EPA Other Test Method 10, see US EPA 2006) using open-path technology, with statistical and computational modelling in conjunction with meteorological monitoring. These techniques can

be used to provide flux measurement and horizontal methane mapping to identify hotspots.

- Discrete sampling campaigns, using multiple monitoring points with high mast sampling and vehicle-mounted analyser transects (car and/or aircraft).

Determination of the concentration of methane is typically performed by FID or CEAS. Considerations in relation to methane concentration measurements are set out in Section 5.3.2 above. The aim in many modern studies is to speciate the VOCs to look for ratio fingerprints to facilitate source apportionment using grab sampling techniques, as discussed in Section 5.3.2.

Short-term intensive surveys using monitoring techniques such as the open-path methods and discrete sampling can be used to provide short-term flux and concentration profiles. These systems can also be used for long-term measurement, although this is more often achieved by the use of continuous discrete sampling systems such as FID or a CEAS-based system.

These measurements can be used with tracer gas correlation and inverse-dispersion modelling (such as the backward Lagrangian stochastic inverse-dispersion modelling technique or the CMAQ ‘adjoint’ model) to locate and characterise possible source terms. The UK has increasing experience of regional-scale models such as the CMAQ model, which can run inverse models to locate potential source terms. The CMAQ infrastructure in the UK is linked to advanced independent meteorological forecasting and is the basis of current UK pollution prediction forecasting. Other techniques such as radial plume and range resolution mapping using open-path optical techniques can be used for methane flux assessment.

These methods have the disadvantage of needing to cope with possible complex source terms. A methodology for doing this is provided in US EPA (2011b).

The following sections set out study design and measurement techniques which may be appropriate for flux measurements.

5.5.2 Radial plume mapping

Radial plume mapping (RPM) is defined in US EPA Other Test Method 10 (OTM10) *Optical remote sensing for emission characterisation from non-point sources* (US EPA 2006). It is used to determine emission fluxes over a large area with the aim of identifying any significant sources (‘hotspots’). It is development from the classical line of site open-path measurement. What defines the method is not the technology used (OP-FTIR, OP-TDLAS, UV-DOAS and DIAL can all be used) but how it is used.

OTM10 provides methodologies for characterising gaseous emissions from non-point pollutant sources using multiple-beam configurations of open-path, path-integrated optical remote sensing (PI-ORS) systems. This enables the detection of ‘hotspots’ and determination of emission fluxes. The protocol describes three methodologies:

- Horizontal radial mapping: map pollutants in the horizontal plane used for hotspot determination.
- Vertical radial mapping (VRPM): designed to measure mass flux of pollutants through a vertical plane downwind of a source.
- One-dimensional radial mapping: designed to profile pollutants along a line of sight.

In simple operation, an open-path system provides the concentration along the line of sight of the system. This gives information along the single plane at a single distance. The VRPM extends this approach to give an estimation of the rate of gaseous emissions from an area of fugitive source. A downwind vertical plane is used directly to measure the gaseous flux. Wind speed and direction measurements must be recorded for flux calculations. The measurements are then processed to provide a multi-path concentration, mapping a volume of air.

Application of this method is complex and would normally be applied as a stand-alone specialist scientific study rather than as a routine regulatory or management tool.

These methods rely on quality meteorological measurements. This would ideally require a good quality weather station tower. The components of the weather to be measured are not just wind speed and direction but also:

- horizontal wind speed and direction;
- vertical wind speed and lateral turbulence;
- relative humidity and dew point;
- solar radiation;
- atmospheric pressure.

The protocol recommends measurement of meteorological conditions at a minimum of two heights (usually at 2 and 10 m) for a more accurate interpolation and extrapolation through the height of the vertical plane. If only a single weather station is available, one wind monitor can be used at mid-height (3–5 m) to represent the average wind of the entire vertical plane.

The monitoring equipment would normally be set up downwind of the source. Using OP-FTIR as an example, the transmitter/receiver would be set up with several mirrors to measure the following:

- Emission hotspots. Using the horizontal component, several mirrors, which become the path-determining component, can be arranged as a radial pattern at different distances. The transmitter/receiver is targeted at each mirror in turn. The data are used to calculate a path-integrated concentration along all these paths and can be combined to provide a two-dimensional concentration contour map of the area assessed. This will show up any hotspots.
- Methane fluxes. Using the vertical component, a configuration of three mirrors or five or more mirrors is used. The three-mirror configuration is mounted on a tower and the path-integrated concentration is determined for each mirror. The beam path would be perpendicular to the mean wind direction of the source under investigation. Hence, combined with meteorological data, a two-dimensional cross-section of any plume can be measured and the methane flux calculated. A more complex mapping of the cross-section concentration can be achieved using additional ground beam mirrors at different distances to calculate a one-dimensional ground level flux.

The one-dimensional component of this can be used as a stand-alone fenceline assessment technique to provide a fenceline concentration profile

The limitations will be those of the instrument type used; typically, inclement weather (e.g. high winds, poor visibility) can have a significant effect on the method performance, although very low winds may also hinder the measurement. Complex terrain in the area and distance from the source can also influence the outcome.

This method relies on very accurate systems control to move the sensor to each of the receptor points in turn. This significantly increases the costs of purchasing and operating such systems.

The strengths of this method are:

- high spatial and temporal resolution;
- direct determination of emission rates;
- wide scale characterisation;
- scope for real-time data.

An example of the application of this method is a project undertaken in 2008 in the USA to undertake the measurement of VOC upstream from oil and gas facilities in Colorado. The project used two open-path Fourier transform systems in a four-corner configuration. The data were collected using three beams for each of the four flux planes (i.e. each side of the box surrounding the site). The four flux planes provided continuous measurement coverage under changing wind directions and strengths.

5.5.3 LIDAR-based plume mapping using path-integrated differential absorption (DIAL)

This is one of two major variations of the standard radial plume mapping approach, which are often considered completely separate techniques. A major limitation is the use of multiple mirrors or path-determining components and the level of calculations required to turn these measurements into two-dimensional concentration profiles. Using a system that does not need to rely on the use of mirrors would have significant advantages. This variation of radial plume mapping is often termed a 'range-resolved measurement'.

Based on the principle of elastic backscatter light detection and ranging (LIDAR), a beam consisting of two wavelengths is pulsed by the emitter; a photon is absorbed by an atom in the atmosphere, which immediately emits another photon at the same wavelength. One wavelength will be in the absorption spectrum of methane but the other wavelength will not, so there will be a measurable attenuation between the two. The difference between the returning signals will be proportional to the concentration of methane.

The important difference here is that the system will also determine the distance, allowing a two-dimensional profile to be determined by scanning at different heights. This, coupled with the range of the laser-based system of 1–3 km, will enable large cross-sectional areas to be assessed.

These data, coupled with meteorological data across the measurement plane, are used to derive the methane flux.

The strength of the method is the high-resolution concentration profile that can be compiled in a relatively short time period. The method does not rely on additional reflectors or sensors, and it can be configured to measure a limited number of other gases, giving it the ability to be used in conjunction with a tracer gas surrogate, for localised validation and use in tracer gas correlation.

The major limitation of this method is the global scarcity and cost of operational DIAL systems.

5.5.4 Solar occultation flux measurement

This is a further variation of the basic radial plume mapping method. In this case, a broadband IR or UV spectrum from the Sun is used as the source, measured by a ground-based spectrometer such as a passive FTIR. The system requires a means to track the Sun, maintain the optimal orientation for the sensor and record the position of the sensor on the ground (GPS).

As with the other remote flux assessment techniques, this method will also need local quality meteorological measurements.

The method has the advantage of being vehicle-based, so measurements can be taken while mobile. Combining these data it is possible to assess a very large area. However, the advantage gained from using the Sun can also be a major disadvantage in poor visibility or unstable wind conditions.

This method simplifies the instrumentation but does have a number of drawbacks in that the broadband IR or UV source will be the whole sky, with assessment along the entire length of the air column, resulting in a loss of spatial resolution compared with the other techniques. It is sensitive to cloud cover and wind speed.

5.5.5 Tracer gas correlation

This technique can be used in conjunction with discrete measurements, mobile measurements and with open-path techniques and technologies. The concentration of methane is measured together with the concentration of a tracer gas that is being released at a known constant rate. This aids in the determination of the emission flux of methane as an alternative to dispersion modelling where complex meteorological conditions may exist.

The tracer gas needs to be chemically stable with no other significant local sources so that the emission is stable. With methane, the tracer gas is typically acetylene. A tracer gas is released to mix with the plume being assessed and is detected by spectroscopic methods. Typically the technique has used fixed point or mobile measurement. This can take advantage of long-term fixed measurements such as NOAA mast stations in the USA and mobile units in vehicles (Pétron et al. 2012).

In order to determine a methane flux, single or point tracer measurements would be combined with high-resolution meteorological measurements (e.g. of the 3-dimensional wind field) and with detailed release logs and field notes. Any mobile units would need high-resolution GPS systems. Data processing is critical.

This approach does provide more accurate emission flux estimation but has significant logistical considerations.

5.6 Design of monitoring surveys

This section sets out factors relevant for consideration when designing on-site, boundary-fence or off-site monitoring surveys.

5.6.1 Priorities for source monitoring

In the light of the discussion in Chapter 3, it is recommended that source monitoring is focused on the following components:

- completion phase
- flowback water handling, storage and processing units
- flares
- production phase
- compressors
- dehydrator vents

- dehydrator pumps
- pneumatic device vents
- well abandonment
- wellhead, particularly any wells where there is reason to consider that well bore integrity or concrete seals may have been compromised

5.6.2 Off-site receptors/assessments

The off-site receptors that may need to be considered for ambient monitoring and assessment include:

- The 'fenceline' of the site, where measured concentration transects may be used to support the estimation of net emission fluxes from the whole site.
- Nearby residential areas, where measurements may be more localised (rather than transects).
- Locations of maximum off-site impact, which may be at the fenceline for near-ground-level releases, or more distant for elevated (above ground-level) releases or for situations where methane emissions experience plume rise.
- Background locations where the level of methane due to other sources may be determined. This may be particularly useful as a survey to be carried out before operation of a shale gas exploration well pad.
- Local air cavities where methane derived from unconventional gas exploratory operations may accumulate (e.g. the headspaces of local boreholes).

Each well pad may have unique receptors, but they will all have a permit boundary, around which it will be possible to undertake a 'fenceline' measurement. Such measurement is relevant to regulation and national reporting, supporting the estimation of the net emission flux from the whole site.

Away from the fenceline, residential areas need to be considered from the point of view of potential localised concentrations affecting members of the public in conjunction with locating possible maximum off-site impact. Maximum impact could be at the fenceline for near-ground-level releases, or more distant for elevated releases or for situations where methane emissions are released under high pressure or undergo a plume rise. In a remote area, this would be less of an issue than in a more densely populated environment.

Methane releases from unconventional gas operations may accumulate in underground voids (e.g. basements) where they could be hazardous i.e. an explosion risk. Methane accumulation could be the result of a short-term activity, but once the methane has accumulated underground it may persist as a long-term hazard. Operators should take appropriate precautions when they are undertaking monitoring or other activities where methane could have accumulated. Precautions are not only necessary for operators, but also for others who may be exposed to such underground methane accumulations.

The risks need to be assessed and managed in the light of site-specific geographical, geological and hydrological factors e.g. the proximity of well pad(s) to boreholes and houses. The risks may continue after gas operations have ceased – in the same way as the risk of methane migration from a landfill can continue after a landfill has closed. It is therefore important to continue to bear such risks in mind, and to maintain liaison with the Health and Safety Executive.

5.6.3 Off-site flux analysis methods

Offsite-measurements of airborne methane fluxes from a shale gas site can be analysed using inverse dispersion modelling methods, in order to attribute fluxes to sources. This type of analysis needs high-resolution meteorological data e.g. measurements of 3-dimensional wind fields. The attributions made can be confirmed by considering what other hydrocarbon species are emitted by particular sources, and then measuring if these species occur in the correct proportions alongside methane in the airborne fluxes. This would be useful in apportioning multiple sources, as described in the Environment Agency R&D Report *Monitoring and control of fugitive methane from unconventional gas operations* (Environment Agency 2012a).

The three-dimensional differential absorption LIDAR (3D-DIAL) method can be used to assess a complete site to compare upwind and downwind methane fluxes so that incremental flux due to the emissions from the site can be determined. This provides a very comprehensive methane flux assessment. It is not suitable for routine or long-term measurements, but can be used to provide a spot check during clear and calm weather conditions.

For locations away from the fenceline, such as hotspots and possible methane build up in subterranean cavities or enclosed spaces, portable or fixed instrumentation can be used. Suitable equipment may include FLIR systems, FID, FTIR and CEAS. FLIR has not been proved in this application, but fixed and portable versions of the other instrument types are available, and portable versions will be adequate for this task.

A portable system would be required for enclosed building and basement assessment, but where there are known risks then the methodology should include a preliminary assessment with LDAR-type equipment (such as a hot bead probe) to test the explosive potential of the cavity prior to using equipment that is not intrinsically safe. Such portable equipment may also be suitable for walkover surveys if required.

Use of the more complex and detailed LIDAR measurement methods to give three-dimensional plume mapping may be useful from a research point of view, but is only likely to be relevant for use in mapping off-site levels of methane in infrequent cases, if at all.

6. Methane monitoring techniques and packages

The selection of monitoring packages, informed by the priority of site and environmental factors, is discussed in Chapter 4. Methane monitoring techniques are discussed in Chapter 5. In Table 8, techniques are mapped to the monitoring packages suggested in Chapter 4. If a survey is required, the operator or regulator could select from the suite of monitoring techniques listed as appropriate for the monitoring package. This would then be used to develop a site-specific monitoring programme, as described in Section 4.3.

Table 8: Monitoring package description

Package		Technique 1	Technique 2	Technique 3
A1	Site: low priority Environmental: low priority Approach 1: On-site surveillance	LEL meter	FID in the vicinity of any suspected source	
A4	Site: low priority Environmental: low priority Approach 4: Off site	FID		
B1	Site: medium priority Environmental: low priority Approach 1: On-site surveillance	Site scanning with FID	Site scanning with FLIR	
B2	Site: medium priority Environmental: low priority Approach 2: On-site source	LDAR with FID	LDAR with FLIR	
B3	Site: medium priority Environmental: low priority Approach 3: Site boundary	Boundary transect with FID	Boundary transect with NDIR	
B4	Site: medium priority Environmental: low priority Approach 4: Off site	FID		
C1	Site: high priority Environmental: low priority Approach 1: On-site surveillance	Site scanning with FID	Site scanning with FLIR	Site scanning with NDIR
C2	Site: high priority Environmental: low priority Approach 2: On-site source	LDAR with FLIR	LDAR with NDIR	
C3	Site: high priority Environmental: low priority Approach 3: Site boundary	Boundary transect with NDIR	Boundary transect with DIAL	Boundary transect with CEAS
C4	Site: high priority Environmental: low priority	Off-site survey with	Off-site survey with	

Package		Technique 1	Technique 2	Technique 3
	Approach 4: Off site	FID	NDIR	
D1	Site: low priority Environmental: high priority Approach 1: On-site surveillance	LEL meter	FID in the vicinity of any suspected source	
D3	Site: low priority Environmental: high priority Approach 3: Site boundary	Boundary transect with FID	Boundary transect with NDIR	
D4	Site: low priority Environmental: high priority Approach 4: Off site	Off-site survey with FID	Off-site survey with NDIR	Off-site survey with FLIR
E1	Site: medium priority Environmental: high priority Approach 1: On-site surveillance	Site scanning with FID	Site scanning with FLIR	Site scanning with NDIR
E2	Site: medium priority Environmental: high priority Approach 2: On-site source	LDAR with FID	LDAR with FLIR	LDAR with NDIR
E3	Site: medium priority Environmental: high priority Approach 3: Site boundary	Boundary transect with NDIR	Boundary transect with FLIR	Array monitoring + reverse modelling
E4	Site: medium priority Environmental: high priority Approach 4: Off site	Off-site survey with NDIR	Off-site survey with FLIR	Array monitoring + reverse modelling
F1	Site: high priority Environmental: high priority Approach 1: On-site surveillance	Site scanning with FLIR	Site scanning with NDIR	
F2	Site: high priority Environmental: high priority Approach 2: On-site source	LDAR with FLIR	LDAR with NDIR	
F3	Site: high priority Environmental: high priority Approach 3: Site boundary	Boundary transect with NDIR	Boundary transect with DIAL	Boundary transect with CEAS
F4	Site: high priority Environmental: high priority Approach 4: Off site	Off-site survey with DIAL	Off-site survey with CEAS	Array monitoring + reverse modelling

Within these packages, there is considerable opportunity for survey design to be specified appropriately to the scale of the issue of potential concern. Survey duration, sample numbers, monitoring/sampling locations etc can be adapted to the site-specific circumstances. For example, if the site is identified as a high priority because of a specific item of plant which has been found to malfunction, it would be appropriate for on-site source monitoring to be focused specifically on this item of plant.

As noted in Section 2.3, it is important to liaise with the Health and Safety Executive during the design of monitoring surveys to ensure that measurements are complete and avoid duplication. It is also important to liaise with local authorities during the design and implementation of off-site surveys in order to secure the benefits of local knowledge and take advantage of any potential opportunities for joint working.

7. Example monitoring programmes

7.1 Introduction

This chapter illustrates how the monitoring regimes described in previous chapters could be specified and applied in practice, providing hypothetical examples of situations that the Environment Agency could potentially need to address. In Section 7.2, the use of on-site monitoring techniques in the hydrocarbons industry is discussed, and Section 7.3 describes the use of off-site monitoring. On-site monitoring is widespread within a wide range of industrial processes. In contrast, off-site monitoring is typically targeted only to those situations where there is considered to be an enhanced risk to receiving environments, and/or where there is significant public interest.

Section 7.4 describes the development of an example monitoring survey for a lower risk site, and Section 7.5 provides an example monitoring programme for a higher risk site.

7.2 On-site monitoring in the hydrocarbons industry

An on-site ambient air monitoring programme is normal practice at operational refinery sites. This typically involves a site walkover survey using an appropriate monitoring system, and forms part of the site LDAR programme.

Refinery operators typically use American Petroleum Institute (API) methods for developing methane emissions estimates. Site walkover surveys have in the past used handheld flame ionisation detection (FID) instrumentation, with bagging and sampling to characterise emissions from any potentially significant sources identified. More recently, handheld forward-looking infrared (FLIR) camera systems have become more widely used as a state-of-the art system for identifying leaks and unexpectedly high discharges. FLIR cameras do not provide quantification of an emission, but can provide a useful guide to further investigation using bagging methods if appropriate. Light detection and ranging (LIDAR) systems have generally been found to be less useful for identifying release points at complex refinery sites.

7.3 Off-site monitoring

Historically, the Environment Agency has required off-site monitoring for installations such as large-scale combustion processes. Examples of this include:

- Monitoring to demonstrate compliance with the UK 15-minute mean sulphur dioxide standard in relation to emissions from coal-fired power stations and oil refineries.
- Monitoring to provide data to support the evaluation of potential impacts of acid and nitrogen deposition at European habitat sites in relation to emissions from coal-fired power stations.
- Monitoring to provide verification of dispersion model forecasts in relation to emissions from waste to energy facilities.

Additionally, the Environment Agency makes appropriate use of off-site monitoring by other bodies, where/when available, typically in order to assess the off-site impacts of regulated sites. For example, the Environment Agency has made use of data provided by local authorities from monitoring stations close to steelworks and waste facilities.

Any monitoring programme set by a regulator as an operational requirement must have regard to the applicable guidance and constraints of the relevant regulatory mechanism. For example, at the Bacton gas compressor station in Norfolk, based on the relevant BAT reference note (BREF), methane monitoring was accorded a relatively low priority. Consequently, the present report document sets out considerations which could be used to support the development of methane monitoring packages at unconventional gas installations, but regulators and operators should have regard to other relevant guidance and regulatory requirements.

Off-site methane monitoring is not normally carried out at existing refinery facilities in the UK. Off-site monitoring may be appropriate in some circumstances, for example for new industries, or where there are reasons to be concerned about emissions from a particular facility, such as persistent and extensive reports of odours in the surrounding area.

7.4 Example: Lower risk site

This section provides an example of how a site-specific monitoring package could be specified for a lower risk site. The design of the monitoring package takes into account both on-site (or 'operational') factors, and off-site (or 'environmental') factors.

Example: An application has been received for the first exploratory site in a new shale gas field. The proposed development comprises a well pad located in an agricultural area with cattle farms in close proximity to the exploratory site. An operational landfill site is located 4 km north-east of the site. At present, there is little information on geological conditions, but overlying rock is considered likely to be impermeable, with little evidence of previous drilling in the surrounding area. The application highlights the findings of a pre-existing UK-wide methane monitoring programme, which provides an indicative value for the background methane concentration.

The operator has carried out preliminary calculations of emissions using emissions factors developed for the conventional hydrocarbons industry. These calculations do not themselves give cause for concern, but cannot be verified as appropriate for the shale gas site, as methods and data have not yet been published for estimating methane emissions from unconventional gas facilities in the UK.

Sections 7.4.1 and 7.4.2 set out how a monitoring survey could be developed.

7.4.1 Example operator requirement (lower risk site)

This section provides an example of how an operator requirement could be specified.

Example: A written report shall be submitted to the Environment Agency for approval. The report shall contain a protocol for a methane monitoring programme in accordance with guidance set out in the Environment Agency report 'Considerations for quantifying fugitive methane emissions from unconventional gas operations' (2013). The monitoring programme is required to establish baseline of methane levels and assess changes in methane concentrations during exploration, completion and production to verify the findings of preliminary calculations. The report shall contain a timescale enabling approval and implementation of the baseline monitoring component of the programme prior to the commencement of drilling operations.

7.4.2 Example operator response (lower risk site)

This section provides an example of how an operator could provide a response to the Environment Agency methane monitoring requirement.

Example: In accordance with Environment Agency report 'Considerations for quantification of fugitive methane emissions for unconventional gas operations' (2013), the site methane monitoring requirement was classified as follows:

Classification	Reasoning
On-site factors: medium priority	Operational factors for this development are considered to be medium due to the uncertainty associated with exploration of a new shale gas field. The scale of operations at the proposed well pad is within the expected range of facilities anticipated to be developed in the UK.
Environmental factors: low priority	Environmental factors for this development are considered to be low. This reflects the low population density in the local area, and the absence of potentially confounding sources of emissions to air.
Monitoring package B was identified for this site. Approaches B1, B2, B3 and B4 need to be considered.	

Approach B1: on-site surveillance

i. Walkover monitoring of methane prior to commencement of drilling using FID technique or similar on three occasions. Data collected during methane monitoring before the site is operational will allow the establishment of baseline of methane levels and identifying specific sources emitting methane within the site boundary. One of the walkover surveys will be carried out when the wind blows from the north-east, and will extend to the upwind and downwind site boundaries, in order to enable the potential influence of the landfill site on the levels of methane at the exploratory site to be investigated.

ii. Daily site walkover monitoring of methane during drilling and hydraulic fracturing of exploration wells using FID (or similar) technique in order to establish if significant methane emissions occur during well drilling and hydraulic fracturing.

iii. Daily site walkover monitoring of methane during completion of exploration stage using FID (or similar) technique in order to establish if recovered fracturing fluid and produced waters from shale formations give rise to significant levels of methane.

iv. Weekly site walkover monitoring of methane during first month of production using FID technique or similar. Weekly data collection during first month of production at wellhead and local production equipment to allow any leaks from specific production equipment to be identified. The findings of this survey to be evaluated in the light of the site LDAR programme and to be taken into account in any relevant equipment performance acceptance test.

v. Standard LDAR programme, specified under other regulatory provisions.

A report on B1(i) to be submitted to the Environment Agency at least 1 month before commencement of drilling activity at the site. A report on B1(ii) and B1(iii) to be submitted within 1 month of well completion. A report on B1(iv) to be submitted within 2 months of commencement of production. All reports to include information on the activities taking place on the site for the duration of the survey. These reports will include a review of the classification and proposed monitoring programme in the light of the survey findings.

Approach 2: B2 – on-site sources

Not required other than standard LDAR programme, provided that on-site methane emissions sources are not identified during on-site surveillance programme (B1 above).

Approach 3: B3 – boundary fence

Not required, as site inventory not needed during exploration phase.

Approach 4: B4 – off site

Not required, as no sensitive receptors were identified within close proximity of the proposed site.

7.5 Example: Higher risk site

This section provides an example of how a site-specific monitoring package could be specified for a higher risk site.

Example: An application has been received for the first exploratory site of 3.6 hectares in a new shale gas field. The application covers a well pad with up to 10 multi-stage horizontal wells. A residential area, including an old people's home and a nursery, is located in close proximity to the exploratory site. The operator has no previous record of operations in the UK. The rock overlying the shale formation is considered likely to be impermeable, with a history of minerals extraction in the surrounding area.

The application draws on the operator's experience in the USA and in a small number of exploratory wells drilled elsewhere in the UK, and highlights the uncertainties associated with conditions likely to be encountered in this new development. The operator has carried out preliminary calculations of methane emissions and provided this information with the application.

Sections 7.5.1 and 7.5.2 set out how a monitoring survey could be specified as part of the permitting process, should this be appropriate.

7.5.1 Example operator requirement (higher risk site)

This section provides an example of how an operator requirement could be specified.

Example: A written report shall be submitted to the Environment Agency for approval. The report shall contain a protocol for a methane monitoring programme in accordance with guidance set out in the Environment Agency report 'Considerations for quantifying fugitive methane emissions from unconventional gas operations' (2013). The monitoring programme is required to establish baseline methane levels and assess changes in methane concentrations during exploration, completion and production to verify the findings of preliminary calculations. The report shall contain a timescale enabling approval and implementation of the baseline monitoring component of the programme prior to the commencement of drilling operations.

7.5.2 Example operator response (higher risk site)

This section provides an example of how an operator could provide a response to the Environment Agency methane monitoring requirement.

Example: In accordance with Environment Agency report 'Considerations for quantification of fugitive methane emissions for unconventional gas operations' (2013), the site methane monitoring requirement was classified as follows:

Classification	Reasoning
On-site factors: medium priority	Operational factors for this development are considered to be medium. This is a balance between the absence of prior problems with this operator due to a lack of experience, and the uncertainty associated with exploration of a new shale gas field. The scale of operations at the proposed well pad is within the expected range of facilities anticipated to be developed in the UK.
Environmental: high priority	Environmental factors for this development are considered to be high. This reflects the proximity to the residential population including vulnerable people in the local area.
Monitoring package E was identified for this site. Approaches E1, E2, E3 and E4 need to be considered.	

Approach E1 – on-site surveillance

i. Walkover monitoring of methane prior to commencement of drilling using FID technique or similar on three occasions. Data collected during methane monitoring before the site is operational will allow the establishment of baseline methane levels and identification of specific sources emitting methane within the site boundary. One of the walkover surveys will be carried out when the wind blows from the north-east, and will extend to the upwind and downwind site boundaries, in order to enable the potential influence of the landfill site on the levels of methane at the exploratory site to be investigated.

ii. Daily site walkover monitoring of methane during drilling and hydraulic fracturing of exploration wells using FID (or similar) technique in order to establish if significant methane emissions occur during well drilling and hydraulic fracturing.

iii. Daily site walkover monitoring of methane during completion of exploration stage using FID (or similar) technique in order to establish if recovered fracturing fluid and produced waters from shale formations give rise to significant levels of methane.

iv. Weekly site walkover monitoring of methane during first month of production using FID technique or similar. Weekly data collection during first month of production at wellhead and local production equipment to allow any leaks from specific production equipment to be identified. The findings of this survey to be evaluated in the light of the site LDAR programme and to be taken into account in any relevant equipment performance acceptance test.

v. Standard LDAR programme, specified under other regulatory provisions.

A report on E1(i) to be submitted to the Environment Agency at least 1 month before commencement of drilling activity at the site. A report on E1(ii) and E1(iii) to be submitted within 1 month of well completion. A report on E1(iv) to be submitted within 2 months of commencement of production. All reports to include information on the activities taking place on the site for the duration of the survey. These reports will include a review of the classification and proposed monitoring programme in the light of the survey findings.

Approach E2 – on-site source

i. If on-site surveillance (E1) identifies a specific source giving rise to problematic levels of methane, further investigation of this source will be carried out using a combination of LDAR with FID monitoring, LDAR with FLIR monitoring, or LDAR with NDIR monitoring.

ii. Source monitoring will not be required if on-site surveillance (E1) does not identify any specific sources giving rise to problematic levels of methane.

A report on E2(i) to be submitted to the Environment Agency within 1 month of identification of any problem source. This report will include a review of the classification and proposed monitoring programme in the light of the survey findings.

Approach E3 – boundary fence

Not required as site methane inventory not needed during exploration phase.

Approach E4 – off site

i. Walkover survey at nearby sensitive locations (old people's home, nursery, some residential properties) using NDIR or FLIR or a combination of monitoring and modelling techniques on three occasions prior to commencement of drilling.

ii. Monthly walkover survey at nearby sensitive locations (old people's home, nursery, some residential properties) using NDIR or FLIR or a combination of monitoring and modelling techniques during completion, and during the first 6 months of production.

A report on E4(i) to be submitted to the Environment Agency at least 1 month before commencement of drilling activity at the site. An interim report on E4(ii) to be submitted within 3 months of commencement of production. A final report on E4(ii) to be submitted within 8 months of commencement of production. All reports to include information on the activities taking place on the site for the duration of the survey. These reports will include a review of the classification and proposed monitoring programme in the light of the survey findings.

8. Related issues

8.1 Introduction

This section collates a number of supplementary issues that may arise when defining and applying monitoring methods for fugitive methane.

8.2 Ancillary information requirements

8.2.1 Selection of units

Industry standard practice in the USA is to use a range of imperial data for reporting information associated with unconventional hydrocarbons. It is recommended that metric units (as listed below) are used for reporting, to avoid confusion in stakeholders unfamiliar with the US industry standards, and to facilitate benchmarking and use alongside other datasets.

- Volume quantities (e.g. gas volumes or oil volumes): cubic metres
- Mass quantities: milligrams/kilograms/tonnes etc as appropriate
- Methane concentration: parts per million by volume, or milligrams per cubic metre. Temperature should be identified when reporting concentration in units of mg/m^3
- Global warming potential: tonnes carbon dioxide equivalent (100-year time horizon)
- Temperature: Kelvin (alternatively degrees centigrade)
- Energy: kilojoules or megajoules (alternatively megawatt-hours)
- Power: kilowatts or megawatts

Useful conversion factors are provided in Table 9.

Table 9: Conversion factors

To convert from…	to…	Multiply by
short tons	tonnes	0.907
cubic feet	cubic metres	0.0283
million cubic feet (MMcf)	thousand cubic metres	28.3
British thermal units	kilojoules	1.055
thousand British thermal units (MBTU)	kilowatt-hours	0.293
mg/m^3 methane at 273K	ppm methane	0.71
tonnes methane	tonnes carbon equivalent	25

8.2.2 Accompanying information

When carrying out a survey of methane as described in the preceding sections, it is important to ensure that a full range of relevant data is recorded to enable the study findings to be properly interpreted, and to gain maximum value from the measurements. This is particularly important when the data are used to infer a site emission rate.

Issues to consider when gathering data to support assessment of methane emissions from unconventional gas installations were considered in the Environment Agency R&D Report *Monitoring and control of fugitive methane from unconventional gas operations* (Environment Agency 2012a). The following items were highlighted for recording to support inventory estimates, and are also relevant in relation to methane monitoring survey data:

- Number of wells drilled; depth and description of vertical depth and directional/horizontal extent.
- Number and timing of hydraulic fracturing activities conducted during survey (number of fracturing stages per well; volume of fluid used for each stage).
- Number and timing of well completions during survey.
- Number of well workovers during survey.
- Gas production from each well and across the installation during survey.
- Volume of wastewater produced and treated (on site or off site).
- Flowback fluid volumes and composition during survey.
- Any unusual operating conditions during survey.
- Description of any reduced emissions completion methods used.
- Description of instrumentation techniques used for methane measurements.
- Relevant operator and laboratory accreditations/certification for measurements and analytical techniques.

Additionally, it is recommended that the following data should be recorded during any methane survey work to be reported to the Environment Agency under the terms of the site operating permit:

- The section of the permit, application plan or other document which the monitoring is designed to fulfil.
- Meteorological conditions (wind speed, wind direction, air temperature, atmospheric pressure, precipitation, cloud cover), including any unusual weather conditions which might affect emissions or dispersion such as temperature inversion or foggy conditions.
- The presence of any potentially confounding sources of methane which could account for the measured levels.

8.3 Compliance assessment

The normal route for the specification of compliance benchmarks is via the specification of BAT reference notes (BREFs) under the auspices of the European Commission. This process enables emission limits to be set via the permitting system, typically as concentration limits or less commonly as mass emissions per unit of production or per unit time.

At this stage, information to enable methane emissions per site to be benchmarked is limited. Some information on expected methane emissions from operational plant is provided in Section 3.5. For example, this indicates that emissions of methane from a compressor plant at a four-well pad might be expected to be 116 tonnes per year. If measured emissions from an operational pad are substantially below or above this figure, this would indicate correspondingly low or high levels of concern with regard to this item of plant.

LDAR programmes are required by many permits for operational hydrocarbons facilities in the UK and elsewhere. The US EPA uses methane concentration thresholds of 500 ppm for pumps and 10,000 ppm for valves as the definition of leaks which require intervention and repair (US EPA 2007). Compliance with these benchmarks could be used as the basis for moving from a higher to a lower classification with regard to operational risks. However, such concentration-based benchmarks cannot be used in relation to surveys carried out using techniques such as FLIR cameras. This may require the use of qualitative criteria for identifying when a site can move from one classification to another, such as 'no more than one observable leak during a 3-month period'.

The most helpful criteria for moving from one classification to another are likely to be qualitative but clear and unambiguous in nature. Examples of possible criteria are set out in Section 4.4.

8.4 Reporting

As with any monitoring survey, the report should set out the survey results clearly and comprehensively (e.g. with full data in an appendix to the report and/or provided digitally). The report should set out any interpretation or conclusions drawn from the data. This may comprise a measured or estimated methane emission rate, identification of sources for further investigation, an evaluation of off-site impacts, or other relevant conclusions.

In many cases, the study report will recommend further investigation. For example, the use of less detailed monitoring methods may highlight sources or issues which can be ruled out, and sources which should be investigated further. The need for further monitoring may be identified by evaluation against environmental benchmarks or levels recorded during a background survey. Measured or estimated emissions above those set out in Sections 3.4 and 3.5 of this report may be indicative of a source requiring more detailed investigation. The observation of relatively high emissions compared to other site sources (e.g. by use of a Fourier transform infrared camera) may also be sufficient to trigger further investigation. In particular, if high emissions are observed from a subset of otherwise identical plant at a site, this is likely to be indicative of substandard operating conditions for these units, which should be investigated further.

Uncertainties should be reported alongside data wherever possible.

8.5 Uncertainties

Guidance on dealing with measurement uncertainties is provided elsewhere (e.g. Environment Agency technical guidance notes M2 pp. 17–20, pp. 62–76 and M8 pp. 15–16, p. 25).

In the case of the assessment of fugitive methane emissions at unconventional gas installations, the most significant uncertainties are likely to arise from the transposition of monitoring data from one circumstance to a different set of circumstances (e.g. different site, or the same site at a different time). Uncertainties will arise from variations in emissions over time, and at different stages in unconventional gas exploration/extraction. Uncertainties may be introduced by difficulties in identifying all potential sources of emissions, and by difficulties in translating concentration measurements into quantitative emissions estimates. In this context, measurement uncertainty is important, but it is unlikely to be the most significant source of uncertainty in quantitative emissions estimates made using either site-specific measurements or generic techniques.

9. Conclusions and recommendations

This report is designed to contribute to the development of Environment Agency thinking around the control and monitoring of methane at sites where hydraulic fracturing is used to extract shale gas, and at similar 'unconventional gas' facilities. The report sets out a range of considerations which the Environment Agency can use to help in developing its approach in this important area. Further work will undoubtedly be needed in the implementation of controls, including the design of appropriate monitoring programmes.

Methane monitoring may be useful to support site-specific estimates of methane emissions from unconventional gas operations. Because this is an emerging industry, it may also be useful to obtain methane monitoring data to support the development of generic methane estimation techniques, in a similar way to that which has been carried out for other relevant industry sectors such as conventional gas extraction and landfilling of biodegradable waste.

This report sets out a proposed structured approach to the assessment and (if necessary) monitoring of methane at unconventional gas installations. The report may be considered as a guide to inform the development of best practice monitoring regimes, at the discretion of operators or regulators. It is not intended to explicitly define or replace monitoring strategies set out within the existing permitting framework; indeed, further work would be necessary to translate concepts in this report into requirements that could be implemented in practice. However, this structured approach would represent a practical way of managing the potential environmental effects of fugitive methane emissions from unconventional gas facilities.

There remain substantial uncertainties associated with the potential significance of methane emissions from unconventional gas exploration and production. It is recommended that strategic baseline monitoring at a limited number of representative shale gas and/or coalbed methane exploration sites in the UK and Europe would be beneficial. A study of this nature would inform our understanding of the scale of methane emissions and associated risks/impacts at such sites, and assist in putting any such risks into context with other industry sectors. Such a study would also provide useful generic field data obtained from operations in England and Wales for losses at various stages of operation or from specific apparatus. Similar field surveys have been carried out on behalf of Defra and the Environment Agency in relation to methane emissions from landfill sites. It is recommended that the landfill research programme, and any lessons learned, could be used as the starting point for designing a strategic survey of unconventional gas exploration sites.

At present, there are published methods available for the desk-based estimation of methane emissions from conventional gas installations. It is recommended that the Environment Agency and industry bodies should work together to develop methods and data for estimating emissions from unconventional gas installations, focusing on the key sources identified in Chapter 3. This recommendation is in line with recommendations made in a recent Department of Energy and Climate Change report (DECC 2013a) on *Potential greenhouse gas emissions associated with shale gas extraction and use*, that 'there should be a detailed scientific research programme of methane measurement, aimed at better understanding and characterising sources and quantities of methane emissions associated with shale gas operations' and that 'this research programme should be independent and managed jointly between government and industry. The research should aim, for example, to reduce uncertainty associated with estimates of local methane emissions from shale gas operations and also to guide the optimisation of regulatory monitoring. The research could also provide information on the effectiveness of operators' actions to minimise methane emissions.'

Table 8 of this report summarises how the available methane monitoring techniques could be used to meet different requirements. There are many survey requirements for which there are relatively few monitoring techniques available, and/or for which it may be challenging and potentially expensive to provide measurement surveys. The management of methane at unconventional gas installations will benefit from the development of new techniques and improvement of existing systems. It is recommended that the Environment Agency should keep a watching brief on developments in this area.

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Glossary and abbreviations

Term	Explanation
Abandonment	To permanently close a well, usually after either logs determine there is insufficient hydrocarbon potential to complete the well, or after production operations have drained the reservoir. An abandoned well is plugged with cement to prevent the escape of methane to the surface or nearby aquifers.
Alkane	A particular type of hydrocarbon, formerly called paraffins
ANGA	America's Natural Gas Alliance
Annular space or annulus	Space between casing and the well bore, or between the tubing and casing or well bore, or between two strings of casing.
Aquifer	A zone of permeable, water-saturated rock material below the surface of the Earth capable of producing significant quantities of water.
AXPC	American Exploration and Production Council
BAT	Best Available Techniques/Technology
Biogenic	Of biological origin. This refers to methane that has formed in the present-day biosphere. This methane contains carbon atoms with a recent isotopic signature, which distinguishes it from ancient thermogenic methane
Blowout	An uncontrolled flow of gas, oil or water from a well during drilling when high formation pressure is encountered.
BS	British Standards
CAMS	continuous ambient monitoring system
Carbon dioxide equivalent (CO_2e)	A measure used to compare the emissions from various greenhouse gases based upon their global warming potential. For example, the global warming potential for methane over 100 years is 25. This means that emissions of 1 million tonnes of methane are equivalent to emissions of 21 million tonnes of carbon dioxide.
Casing	Steel pipe placed in a well.

CBM	coalbed methane (see below for definition)
CEAS	cavity enhanced adsorption spectroscopy
CEMS	continuous emission monitoring system
CMAQ	Community Multiscale Air Quality [model]
CNT	carbon nanotube
CO_2	Chemical formula of carbon dioxide.
Coalbed methane	A form of natural gas extracted from coal beds. The term refers to methane adsorbed onto the solid matrix of the coal.
Completion	The activities and methods of preparing a well for production after it has been drilled to the objective formation. This principally involves preparing the well to the required specifications, and running in production tubing and its associated down-hole tools, as well as perforating and stimulating the well by the use of hydraulic fracturing, as required.
Compressor station	A facility that increases the pressure of natural gas to move it in pipelines or into storage.
Condensate	Liquid hydrocarbons that were originally in the reservoir gas and are recovered by surface separation.
Conventional reserve	A high permeability formation (greater than 1 millidarcy) containing oil and/or gas, which can be more readily extracted than hydrocarbons from unconventional reserves. The term ‘conventional gas’ is not always used in accordance with this technical definition, particularly in the USA where a different definition is commonly used, and care must be exercised in the use and interpretation of this term.
CRDS	cavity ringdown spectroscopy
Darcy	A unit of permeability. A medium with a permeability of 1 darcy permits a flow of 1 cm^3 per second of a fluid with viscosity 1 cP (1 mPa·s) under a pressure gradient of 1 atmosphere per centimetre acting across an area of 1 cm^2.
DECC	Department of Energy and Climate Change [UK]
Dehydrator	A device used to remove water and water vapours from gas.

DIAL	differential absorption LIDAR
Directional drilling	Deviation of the borehole from vertical so that the borehole penetrates a productive formation in a manner parallel to the formation, although not necessarily horizontally.
DOAS	differential optical absorption spectroscopy
EN	European Standard
EPR	Environmental Permitting Regulations
FID	flame ionisation detection
Field	The general area underlain by one or more pools.
Flare	The burning of unwanted gas through a pipe.
FLIR	forward-looking infrared
Flowback fluids	Liquids produced following drilling and initial completion and clean-up of the well.
Flux	In this context, the overall flow of methane from an unconventional gas facility, expressed as mass flow per unit time. It may also refer to the flow of methane through a conceptual plane perpendicular to the wind direction located downwind of the facility. In this case, the flux of methane is expressed as mass flow per unit area per unit time.
Formation	A rock body distinguishable from other rock bodies and useful for mapping or description. Formations may be combined into groups or subdivided into members.
Fossil methane/fossil fuel	A natural fuel such as coal or gas, formed in the geological past from the remains of living organisms.
Fracking or fracing (pronounced ‘fracking’)	Informal abbreviation for ‘hydraulic fracturing’.
FTIR	Fourier transform infrared
Gas meter	An instrument for measuring and indicating, or recording, the volume of natural gas that has passed through it.
GPS	global positioning system
Green completion	See reduced emissions completion.

Groundwater	Water in the subsurface below the water table. Groundwater is held in the pores of rocks and can be connate (i.e. trapped in the rocks at the time of formation), from meteorological sources or associated with igneous intrusions.
GWP (global warming potential)	A measure of how much a given mass of greenhouse gas is estimated to contribute to global warming.
H_2O	Chemical formula for water.
Hazardous Air Pollutants	Defined under the US Clean Air Act. See list at http://www.epa.gov/ttn/atw/188polls.html
Horizontal drilling	Deviation of the borehole from vertical so that the borehole penetrates a productive formation with horizontally aligned strata, and runs approximately horizontally.
HSE	Health and Safety Executive
Hydraulic fracturing	The act of pumping hydraulic fracturing fluid into a formation to increase its permeability, for shale this typically requires high fluid volumes and high pressure.
Hydraulic fracturing fluid	Fluid used to perform hydraulic fracturing. Includes the primary carrier fluid, proppant material and all applicable additives.
IAS	infrared absorption spectroscopy
ICOS	integrated cavity output spectroscopy
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
ISO	International Organization for Standardization
LDAR	leak detection and repair
LEL	lower explosive limit
LIDAR	light detection and ranging
Limestone	A sedimentary rock consisting chiefly of calcium carbonate ($CaCO_3$).
MCERTS	Monitoring Certification Scheme

Mcf	thousand cubic feet (equivalent to 28.3 m^3)
Methane	Methane (CH_4) is a greenhouse gas that remains in the atmosphere for approximately 9 to 15 years. Methane is also a primary constituent of natural gas and an important energy source.
millidarcy (mD)	A unit of permeability, equivalent to one thousandth of a darcy.
MMcf	million cubic feet (equivalent to 28,300 m^3)
NDIR	non-dispersive infrared
NOAA	National Oceanic and Atmospheric Administration [US]
NRW	Natural Resources Wales
O_2	Chemical formula for oxygen.
O_3	Chemical formula for ozone.
Operator	Any person or organisation in charge of the development of a lease or drilling and operation of a producing well.
OP-FTIR	open-path Fourier transform infrared
OPRA	Operational Risk Appraisal
OTM10	Other Test Method 10 (of US EPA)
Permeability	A measure of a material’s ability to allow passage of gas or liquid through pores, fractures or other openings. The unit of measurement is the darcy or millidarcy.
Petroleum	In the broadest sense. the term embraces the full spectrum of hydrocarbons (gaseous, liquid and solid).
Photochemical	Formed by the action of sunlight on chemicals in the atmosphere, which then react to produce products that may be harmful. For example the action of sunlight on nitrogen oxides and volatile organic compounds produces ozone which can be harmful to respiration.
PI-DIAL	path-integrated differential absorption light [detection and ranging]
Plays	A surface area or an underground zone where minerals may be available for exploration and production (e.g. hydrocarbons).

Pneumatic	Run by or using compressed air.
Pool	An underground reservoir containing a common accumulation of oil and/or gas. Each zone of a structure which is completely separated from any other zone in the same structure is a pool.
Porosity	Volume of pore space expressed as a percentage of the total bulk volume of the rock.
ppb	part per billion
ppm	part per million
Primary carrier fluid	The base fluid, such as water, into which additives are mixed to form the hydraulic fracturing fluid which transports proppant.
Proppant or propping agent	A granular substance (sand grains, aluminium pellets or other material) that is carried in suspension by the fracturing fluid and that serves to keep the cracks open when fracturing fluid is withdrawn after a fracture treatment.
REC (reduced emissions completion, also known as green completion)	A term used to describe a practice that captures gas produced during well completions and well workovers following hydraulic fracturing. Portable equipment is brought on site to separate the gas from the solids and liquids produced during the high-rate flowback, and to produce gas that can be delivered into the sales pipeline. RECs help to reduce methane, VOC and hazardous air pollutant emissions during well clean-up and can eliminate or significantly reduce the need for flaring.
Reservoir (oil or gas)	A subsurface, porous, permeable or naturally fractured rock body in which oil or gas has accumulated. A gas reservoir consists only of gas plus fresh water that condenses from the flow stream reservoir. In a gas condensate reservoir, the hydrocarbons may exist as a gas, but, when brought to the surface, some of the heavier hydrocarbons condense and become a liquid.
RPM	radial plume mapping
SD	standard deviation
Sedimentary rock	A rock formed from sediment transported from its source and deposited in water or by precipitation from solution or from secretions of organisms.
Seismic	Related to Earth vibrations produced naturally or artificially.

Separator	Tank used to physically separate the oil, gas and water produced simultaneously from a well.
Shale	A sedimentary rock consisting of thinly laminated claystone, siltstone or mudstone. Shale is formed from deposits of mud, silt, clay and organic matter.
Stratum (plural strata)	Sedimentary rock layer, typically referred to as a formation, member or bed.
TDLAS	tunable diode laser absorption spectroscopy
Technically recoverable reserves	The proportion of assessed in-place petroleum that may be recoverable using current recovery technology, without regard to cost.
Thermogenic	Of thermal origin. This refers to methane that has been formed by heating of biological material trapped in geological deposits e.g. of shale. This methane contains fossil carbon atoms with an ancient isotopic signature, which distinguishes it from recent biogenic methane.
Tight formation	Formation with very low (less than 1 millidarcy) permeability.
Tight gas	Natural gas obtained from a tight formation.
Unconventional gas	Gas contained in rocks (which may or may not contain natural fractures) which exhibit in situ gas permeability of less than 1 millidarcy. The term 'unconventional gas' is not always used in accordance with this technical definition, particularly in the USA where a different definition is commonly used, and care must be exercised in the use and interpretation of this term.
US EPA	US Environmental Protection Agency
UV	Ultraviolet
Viscosity	A measure of the degree to which a fluid resists flow under an applied force.
VOC	volatile organic compound
Well bore	A borehole; the hole drilled by the bit. A well bore may have casing in it or it may be open (uncased), or part of it may be cased, and part of it may be open.
Well pad	A site constructed, prepared, levelled and/or cleared in order to perform the activities and stage the equipment and other infrastructure necessary to drill one or more natural gas exploratory or production wells.

	The area directly disturbed during drilling and operation of a gas well.
Well site	Includes the well pad and access roads, equipment storage and staging areas, vehicle turnarounds, and any other areas directly or indirectly impacted by activities involving a well.
Wellhead	The equipment installed at the surface of the well bore. A wellhead includes such equipment as the casing head and tubing head.
Workover	Repair operations on a producing well to restore or increase production. This may involve repeat hydraulic fracturing to re-stimulate gas flow from the well.
Zone	A rock stratum of different character or fluid content from other strata.

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