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Field Measurements of Fugitive Emissions from Equipment and Well Casings in Australian Coal Seam Gas Production Facilities

Report to the Department of the Environment

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Executive Summary

The Australian coal seam gas (CSG) industry has developed rapidly over the last decade and as several liquefied natural gas (LNG) plants currently under construction in Queensland are completed, gas production will increase significantly over the next few years. Fugitive emissions of methane from gas production and processing have the potential to diminish the greenhouse benefits of CSG utilisation compared to other fossil fuels but at present the extent of fugitive emissions from the CSG industry and unconventional gas production more generally is not well understood. Recent reports from the United States have suggested that fugitive emissions from unconventional gas production, especially shale and tight gas, are much higher than previously estimated. However, because of significant differences in production methods and other factors, it is unlikely that emission estimates from U.S. shale and tight gas production are indicative of emissions from Australian CSG operations. To provide quantitative information on emissions from CSG operations, CSIRO and the federal Department of the Environment initiated a project to measure emissions from a range of production wells in Queensland and NSW.

Methane emissions were measured at 43 CSG wells – six in NSW and 37 in Queensland. Measurements were made by downwind traverses of well pads using a vehicle fitted with a methane analyser to determine total emissions from each pad. In addition, a series of measurements were made on each pad to locate sources and quantify emission rates.

Of the 43 wells examined, only three showed no emissions. These were two plugged and abandoned wells and one suspended well that had been disconnected from the gas gathering system. The remainder had some level of emission but generally the emission rates were very low, especially when compared to the volume of gas produced from the wells. The principal methane emission sources were found to be:

- venting and operation of gas-powered pneumatic devices,
- equipment leaks and
- exhaust from gas-fuelled engines used to power water pumps.

The median methane total emission rate (from all sources) for the 43 wells was approximately 0.6 g min^{-1}, and the mean about 3.2 g min^{-1}. Thirty seven wells had total emissions less than 3 g CH_4 min^{-1} and 19 less than 0.5 g min^{-1}. There were however, a number of instances where much higher emission rates were found. The highest emission rate of 44 g min^{-1} was from a vent on a water line at one well although this represented a very minor proportion of gas production. These emission rates are very much lower than those that have been reported for U.S. unconventional gas production.

Gas operated pneumatic devices were installed at some well sites and were occasionally found to be emitting small amounts of methane. These emissions were small (mean emissions rate of 0.12 g min^{-1}) and may reduce even further as gas operated pneumatic systems are replaced by air or electrically operated devices.

Equipment leaks were found on 35 wells with emission rates ranging from less than 1 mg min^{-1} up to about 28 g min^{-1}. The median and mean emission rates from these wells were 0.02 g min^{-1} and 1.6 g min^{-1}, which correspond to emission factors of about 0.1 kg CO_2-e t^{-1} and 2.4 kg CO_2-e t^{-1}, respectively. This range is consistent with the current emission factor of 1.2 kg CO_2-e t^{-1} commonly used throughout the CSG industry to account for equipment leaks for the purposes of reporting emissions under the National Greenhouse and Energy Reporting legislation.

Several of the larger equipment leaks were found at seals on water pump shafts on some wells. However, once identified, well maintenance staff were able to repair some of these leaks on site, which effectively eliminated methane emissions.

Fifteen of the well sites had gas fuelled engines operating at the time measurements were made. The exhaust from most of these engines was found to be contributing to the well site emissions, in several cases

comprising the bulk of methane emissions. From a greenhouse gas accounting perspective, methane in exhaust is not considered to be a fugitive emission but is counted as a combustion emission.

During the field measurements, no evidence of leakage of methane around the outside of well casings was found at any of the wells included in this sample.

Although the well pad emissions were low, a separate, larger source of methane was found on a gas relief vent on a water gathering installation close to one of the wells examined during this study. An indicative estimate of the emission rate from this vent suggested that the source was at least three times higher than the largest well pad emission rate. Similar installations are widespread through the Queensland gas regions and hence further examination is needed to determine the extent of this potential emission source.

The results obtained in this study represent the first quantitative measurements of fugitive emissions from the Australian CSG industry; however, there are a number of areas that require further investigation. Firstly, the number of wells examined was only a very small proportion of the total number of wells in operation. Moreover, many more wells are likely to be drilled over the next few years. Consequently the small sample examined during this study may not be truly representative of the total well population. It is also apparent that emissions may vary over time, for instance due to repair and maintenance activities. To fully characterise emissions, a larger sample size would be required and measurements would need to be made over an extended period to determine temporal variation.

In addition to wells, there are many other potential emission points throughout the gas production and distribution chain that were not examined in this study. These include well completion activities, gas compression plants, water treatment facilities, pipelines and downstream operations including LNG facilities. Emissions from some of these sources are often estimated for reporting purposes using methodology based on emission factors largely derived from the U.S. gas industry. However, reliable measurements on Australian facilities are yet to be made and the uncertainty associated with some of these estimates remains high.

1 Introduction

Coal seam gas (CSG) production is a major and rapidly expanding industry in Australia. During 2011-2012, Australian CSG production was around 247 PJ, which represented about 12 % of total gas production in Australia (BREE, 2013). Since then, production in Queensland alone has increased to more than 264 PJ in 2012-2013 (DNRM, 2014) with production likely to increase even further as several liquefied natural gas plants under construction come on stream. Most Australian CSG is currently produced in Queensland with only one operational project in NSW; however, there are a number of other projects planned for NSW at various stages of approval.

One of the key drivers of increased demand for gas is that greenhouse gas emissions from gas utilisation are usually lower than other fossil fuels (Day et al., 2012). However, because of the much higher global warming potential of methane compared to CO_2, even relatively small proportions of fugitive methane released during the production, processing and distribution of natural gas can reduce this advantage relative to other fuels (e.g. Wigley, 2010; Alvarez et al., 2012).

In the natural gas industry, fugitive emissions are considered to include all greenhouse gas emissions from exploration, production, processing, transport and distribution of natural gas, except those from fuel combustion (IPCC, 2006). However certain combustion processes like flaring and waste gas incineration are also counted as fugitive emissions.

At present the level of fugitive emissions from the Australian CSG industry is not well defined, although individual companies estimate and report their annual emissions under the requirements of the National Greenhouse and Energy Reporting Act 2007 (NGER, see Section 2). These data are used for compiling the Australian National Greenhouse Gas Inventory which currently estimates fugitive emissions from the Australian oil and gas industry to be around 12 Mt CO_2-e per annum (DIICCSRTE, 2013a). About 60 % of these emissions are attributed to venting and flaring, which are in principle amenable to direct measurement; hence the uncertainty on this component may be relatively low. However, other sources such as equipment leaks are frequently difficult to measure so are usually estimated by methodology characterised by very high uncertainty. Despite significant differences in production methods, the national inventory does not at present distinguish between conventional gas production and unconventional sources like shale gas and CSG.

In 2012, the CSIRO reviewed the available scientific and technical literature to assess the current state of knowledge relating to fugitive emissions from unconventional gas production, especially for CSG production in Australia (Day et al., 2012). Most of the information in the public domain at the time was concerned with shale and tight gas production in the United States with virtually none specific to CSG. Up until then, only one study based on actual measurements had been published (Pétron et al., 2012). This group measured methane emissions in the Denver-Julesburg Basin in Colorado and depending on the method used, estimated that the emission rate from the gas field was equivalent to 1.7 to 7.7 % of the gas produced in the region.

Since 2012, several other studies, also from the United States, have been published. Karion et al. (2013) conducted an airborne survey of ambient methane in an unconventional gas field in the Uintah Basin in Utah in the United States. The Karion et al. study yielded emission estimates of between about 6 and almost 12 % of gas production of the region. In a detailed examination of atmospheric methane data from airborne and fixed monitoring stations, Miller et al. (2013) determined the spatial distribution of methane emissions throughout the United States. This study considered all sources of anthropogenic methane emissions, including fugitive emissions from oil and gas production. For the Texas/Oklahoma region emissions from oil and gas production were estimated to be 3.7 ± 2.0 Tg C y^{-1}, which is 4.9 ± 2.6 times higher than the current estimate of 0.75 Tg C y^{-1} in the European Commission's Emissions Database for Global Atmospheric Research (EDGAR).

Both the Miller et al. (2013) and Karion et al. (2013) studies used top-down methodology and did not attempt to determine the specific sources of the methane emissions. Pétron et al. (2012) also used top-down methods which yielded the higher estimates (i.e. ~7.7 % of production) although the bottom-up methodology used by that group gave much lower emission estimates (1.7 %). A bottom-up approach was used by Allen et al. (2013) who examined emissions at the facility level to determine both the rate and route of methane emission. In that study, methane emissions were measured at 190 onshore natural gas sites within the United States, which included 489 production wells (all of which had been hydraulically fractured), 27 well completion flowbacks, nine well unloadings, and four well workovers. One of the key findings of this work was that the measured emissions were generally comparable to the most recent USEPA estimates of emissions from the sources examined, although the relative proportion of emissions from individual categories differed somewhat. For example, emissions from pneumatic devices were significantly higher than current estimates while emissions from well completions were much lower than estimates in the U.S. inventory. Overall, the emissions estimated from the unconventional gas industry corresponded to about 0.42 % of production.

This bottom-up estimate contrasts with the much higher top-down estimates discussed above. The lower emission rate estimated by Allen et al. (2013) may be explained in part by the fact that only production facilities were considered. Emissions from downstream processing, transport and distribution were not included so any emissions from these facilities would be expected to increase this proportion. Another reason for the discrepancy between bottom-up and top-down estimates has been proposed by Brandt et al. (2014) who suggested that a large proportion of emissions may be due to a small number of 'super emitters'. If true, facility level bottom-up measurements may sometimes miss these large emission sources. In addition to gas production facilities, other sources may be contributing to overall emissions, which are not captured by the bottom-up methods. Tait et al. (2013), for example, proposed that drilling and associated activity may induce fracturing of overlying strata thus providing pathways for methane to reach the surface and escape to the atmosphere. Such landscape-scale emissions would be detected by many top-down methods but may be difficult to measure using the bottom-up methodology applied by Allen et al. (2013). However, the Tait et al. (2013) model was based on ambient radon measurements; methane emission rates were not measured so this emission route remains speculative at this stage. Other possible emission sources that could account for the apparent discrepancy between the reported top-down and bottom-up methods are geological sources such as seeps that are often associated with oil and gas fields (Klusman, 1993) or abandoned boreholes (Etiope et al., 2013; Day et al., 2013).

In Australia, limited investigations into fugitive methane emissions from CSG production have been undertaken over the last couple of years. In an initial study that was widely reported, Santos and Maher (2012) surveyed a CSG production region near Tara in Queensland using an instrumented vehicle to measure the spatial distribution of ambient methane concentrations. They measured elevated methane concentrations within the gas field that they suggested may be indicative of fugitive methane release from production activities. More recently, a study of ambient methane levels in the vicinity of CSG production facilities south of Sydney was reported (Pacific Environment Limited, 2014). This study also found elevated methane concentrations near CSG facilities although they concluded that on average, ambient methane concentrations within the gas field were comparable to those in a nearby urban area. However, neither study attempted to measure emission flux and in any case, the presence of other potential methane sources such as cattle feedlots, abandoned boreholes and landfill sites complicated the interpretation of the results. Consequently attempts to attribute sources based on these results remain inconclusive.

Despite the level of recent activity aimed at quantifying emissions from unconventional gas production, the situation remains unclear. The Australian studies reported to date only considered ambient methane concentrations near gas production sites and provide no information on emission flux. While the U.S. studies measured emission rates, widely varying estimates were reported. Moreover, they were concerned with shale and tight gas operations, which are unlikely to be indicative of emissions from Australian CSG production facilities. Due to the lack of quantitative emission data specific to Australian operations, the CSIRO review recommended, among other things, that a series of measurements at CSG production facilities was required to better understand the actual level of fugitive emissions from the Australian CSG

industry (Day et al., 2012). A similar recommendation for emissions measurements was made by Saddler (2012) when reviewing methodology for estimating emissions from CSG production.

As a result of these recommendations, CSIRO initiated a project with the principal aims of (1) developing atmospheric top-down methodology for monitoring and quantifying methane fluxes from CSG production facilities and (2) measuring methane emission fluxes from operational CSG production sites. Shortly after this project commenced, the federal Department of the Environment (then the Department of Climate Change and Energy Efficiency) requested that CSIRO to extend the scope of the field measurements to include an investigation of gas leakage from well casings and equipment located on individual well pads.

In this report we present the results of field measurements made at well sites throughout NSW and Queensland. The specific objectives of these measurements were to:

- quantify methane emissions from individual well pads,
- identify the primary routes of these emissions,
- measure leak rates from individual items of equipment located on well pads and
- determine whether or not methane was leaking from around the outside of well casings and if so, measure the leakage rate.

While wells represent a major segment of the CSG production infrastructure, it is important to note that there are many other components downstream of the wells which have the potential to release greenhouse gases. These include processing and compression plants, water treatment facilities, gas gathering networks, high pressure pipelines and several LNG production facilities currently under construction near Gladstone. In the study reported here, we have only examined emissions from a small sample of CSG wells; none of the other downstream infrastructure has been considered at this stage. However, the ongoing CSIRO research into atmospheric top-down method methodology is aimed at developing techniques for monitoring emissions across the CSG industry more broadly.

2 National Greenhouse Gas Reporting Practices

Before discussing the experimental results of the field measurements it is instructive to consider the methodology currently used to estimate greenhouse gas emissions from CSG wells.

Australian CSG gas producers (along with conventional gas operators) are required to estimate and report their annual greenhouse emissions in accordance with the National Greenhouse and Energy Reporting Act 2007 using methodology prescribed in the National Greenhouse and Energy Reporting (Measurement) Determination 2008. The scope of the Act covers all sectors of the gas industry i.e. production and processing, transmission and distribution, and includes emissions from fuel combustion (e.g. stationary engines at well sites and compression plants) and fugitive emissions (leaks from equipment, venting and flaring).

According to the definition used in the Determination, fugitive emissions associated with natural gas production and processing comprise:

- Emissions from venting and flaring
    - the venting of natural gas
    - the venting of waste gas and vapour streams at facilities that are constituted by natural gas production or processing
    - the flaring of natural gas, waste gas and waste vapour streams at those facilities
- Emissions other than venting and flaring which include
    - a gas wellhead through to the inlet of gas processing plants
    - a gas wellhead through to the tie-in points on gas transmission systems, if processing of natural gas is not required
    - gas processing plants
    - well servicing
    - gas gathering
    - gas processing and associated waste water disposal and acid gas disposal activities

The Determination specifies methodology for estimating emissions from all of these sources; the 'Methods' are broadly classified into four generic categories of varying complexity, which are briefly described below.

- Method 1 is the simplest approach and relies on activity data and an emission factor for the process. The emission factors used in Method 1 are generic and are usually specified in the NGER Determination.
- Method 2 is more specific and uses emission factors based on more detailed data.
- Method 3 is very similar to Method 2 except that the methods are based on internationally accepted standards.
- Method 4 is the direct measurement of emissions.

Some emissions can be directly measured (i.e. Method 4) but often emissions cannot be readily measured so instead, simpler methodology based on the concept of emission factors is used.

Emission factors are average emission rates of a particular gas (i.e. methane but also CO_2 and N_2O if applicable) from a given source. Emissions, *E*, are calculated by multiplying the emission factor, *EF*, by the activity of the process producing the emissions, *A* (Equation 2.1).

$$E = EF \times A \qquad \text{Equation 2.1}$$

Examples of activity are the amount of fuel consumed or the amount of gas produced.

This methodology can yield accurate emission estimates for processes such as fuel combustion where both the emission factor (which is based on the chemical composition of the fuel) and the activity data (i.e. consumption rate of fuel, which is often known to a high level of accuracy) can be well defined. However,

for some fugitive emissions sources such as equipment leaks, emission factors may be subject to very high uncertainty. For instance, the American Petroleum Institute's Compendium of Greenhouse Gas Emissions Methodologies for the Oil and Natural Gas Industry which provides emission factors for calculating emissions from gas production and processing operations, estimates that uncertainties on some emission factors may be as much as 1000 % (API, 2009). One of the reasons for this high level of uncertainty is that emission factors are often based on very limited experimental data.

CSG well pads may release greenhouse gases from a range of sources, all of which are estimated for annual reporting purposes. These sources include fuel combustion in well site engines used to drive water pumps, and fugitive emissions from vents, gas operated pneumatic devices and leaks in equipment. Occasionally, during maintenance operations for example, gas may be flared and this too counts as a fugitive emission that is accounted for. Combustion emissions from engines or flaring are predominantly CO_2 although small amounts of methane (unburnt fuel) and N_2O (produced in the combustion process) may also be emitted. Most of the other non-combustion emissions are methane.

Some emissions from vents can be measured according to Method 4 but because of its simplicity, many CSG operators use the Method 1 approach for estimating most of the other greenhouse gas emissions from well pads. The methods are summarised in Table 2.1.

Table 2.1. Summary of NGER estimation methods for various well pad sources

Classification	Source	Method
Fuel Combustion	Exhaust emissions from well site engines	Emission factor to account for CO_2, CH_4 and N_2O emissions: 51.2 kg CO_2-e GJ^{-1} (CO_2) 0.1 kg CO_2-e GJ^{-1} (CH_4) 0.03 kg CO_2-e GJ^{-1} (N_2O)
Fugitive Emissions	Flare	Emissions factor to account for CO_2, CH_4 and N_2O emissions: 2.7 t CO_2-e t^{-1} (CO_2) 0.1 t CO_2-e t^{-1} (CH_4) 0.03 t CO_2-e t^{-1} (N_2O)
Fugitive Emissions	Equipment leaks	Emission factor of 1.2 kg CO_2-e t^{-1} gas produced
Fugitive Emissions	Gas driven pneumatic equipment	Emission factors specified in the API Compendium (API, 2009)
Fugitive Emissions	Cold process vents	In some cases these can be measured directly (i.e. Method 4). Otherwise estimated using emission factors in API Compendium.

Although most of the methods shown in Table 2.1 are based on the use of emission factors, the level of uncertainty associated with the estimates is quite variable. In the case of emission from engines, the uncertainty is likely to be relatively low provided the amount of fuel consumed is known accurately (which is usually the case). Similarly emissions from flaring can be estimated with reasonable accuracy if the gas

flow to the flare is measured. Emissions from vents are often measured using process instrumentation so these too should be known with a high degree of certainty. Emissions from equipment leaks, pneumatic equipment and vents estimated by emission factors, on the other hand, have higher levels of uncertainty. However, the overall uncertainty of emission inventories is also influenced by the relative contribution of various sources. Hence if a source with high uncertainty comprises only a small proportion of total emissions from a particular sector, the overall level of uncertainty is not greatly influenced by the minor component.

3 Experimental Methods

3.1 Selection of Wells

Five CSG companies provided access to wells in various gas fields throughout NSW and Queensland, which are summarised in Table 3.1. Each company usually provided CSIRO with a list of their wells from which CSIRO staff selected a subset of wells for examination. Because individual companies agreed to participate in the project at different times during the course of the project it was not possible to make a properly randomised selection of wells at the start of the project. Instead, wells were selected on an ad hoc basis in the order that companies agreed to participate. In addition, access to sites due to weather and agreements with landholders determined the selection of wells to some extent.

Factors considered when selecting wells included:

- The production region
- The age of the well, i.e. old to new
- The gas production rate, i.e. from low to high rates
- Whether or not the well had been hydraulically fractured
- The type of surface equipment installed at the well, i.e. pumped or free flowing.

Table 3.1. Participating CSG producers and the gas fields where emission measurements were made.

Company Name	Project Name	Basin	Locality
AGL Energy Limited	Camden	Sydney	MacArthur region, NSW
Arrow Energy Limited	Daandine	Surat	Dalby area, Qld
	Kogan North	Surat	Dalby area, Qld
	Tipton	Surat	Dalby area, Qld
Origin Energy Limited	Talinga	Surat	Chinchilla area, Qld
QGC Pty Limited	Bellevue	Surat	Chinchilla area, Qld
	Berwyndale	Surat	Chinchilla area, Qld
	Berwyndale South	Surat	Chinchilla area, Qld
	Codie	Surat	Chinchilla area, Qld
	Kenya	Surat	Chinchilla area, Qld
	Lauren	Surat	Chinchilla area, Qld
Santos Limited	Fairview	Bowen	Injune area, Qld
	Scotia	Bowen	Wandoan area, Qld

For the purpose of this report, we consider the well pad to be the (usually) fenced area around a well head that contains the surface equipment associated with gas production. This includes the well head, dewatering pump (if fitted), separator, pipework and associated valves and fittings. Also included are vents, (including those installed on water gathering system components on the well pad) and engines used to power dewatering pumps.

The 43 wells selected represent less than 1 % of the 5,000 CSG wells across Australia and therefore may not be representative of the total well population. Nevertheless, it provides a reasonable cross section of the industry covering a range of different producers and geographic locations within the main gas production regions. For comparison, a recent study of well emissions in the U.S. where emissions measurements were made at 489 wells represented only about 0.01 % of U.S. unconventional gas wells (Allen et al., 2013).

3.2 Methane Analysis System

Methane measurements were made using a Picarro Model 2301 Cavity Ring-down Spectrometer $CH_4/CO_2/H_2O$ analyser coupled with a Picarro Mobile Measurement Kit. The resolution of this analyser is < 1 ppbv CH_4 and has very low drift characteristics (Crosson, 2008) so that very small CH_4 perturbations can be reliably detected against the background concentration. Both instruments were mounted in a 19" rack in the rear of a 4WD vehicle (Figure 3.1).

Figure 3.1. Photographs of the field vehicle where the GPS antenna and sonic anemometer are visible on the top of the vehicle (left hand photograph). The methane analyser and a calibration gas cylinder are shown in the rear of the vehicle (right hand photograph).

The Mobile Kit included a GPS receiver and software that allows the spectrometer output to be processed and displayed in GIS software. A two-dimensional sonic anemometer (Climatronics Sonimometer) was also fitted for measuring local wind speed during plume traversing measurements (Section 3.3).

For mobile surveys, the spectrometer was operated continuously as the vehicle was driven. Air was sampled via a ¼" nylon tube from the front of the vehicle about 1 m above ground level. The normal flow rate of sample air to the spectrometer is approximately 100 mL min^{-1}; however, to minimise the lag time between air entering the inlet tube and reaching the analyser, an auxiliary pump in the Mobile Kit was used to increase the flow rate to about 5 L min^{-1}. When used for flux chamber measurements (Section 3.5), the auxiliary pump was bypassed using a three-way valve.

Initially, the instrument was configured to measure CH_4, CO_2 and H_2O simultaneously; however, the sampling rate in this mode was relatively slow with measurements made approximately every 3 s. To increase the spatial resolution during plume traverses, the sampling rate was increased to about 2 Hz by reconfiguring the analyser to measure CH_4 only.

The analyser was calibrated against a reference air sample containing 1.732 ppm CH_4 prepared by the CSIRO Marine and Atmospheric Research GASLAB (Francey et al., 2003). Additional standard gas mixtures of 10.2 and 103 ppm CH_4 in air (BOC Gases Australia) were used for multipoint calibrations.

Although the nominal range of the analyser is 0-20 ppm CH_4, we found that the instrument could reliably measure concentrations well in excess of this level. In one experiment, an Ecotech GasCal dilution system was used to generate gas flows with known CH_4 concentrations up to about 280 ppm. The results of this experiment are shown in Figure 3.2 where the analyser output is plotted against the actual methane concentration.

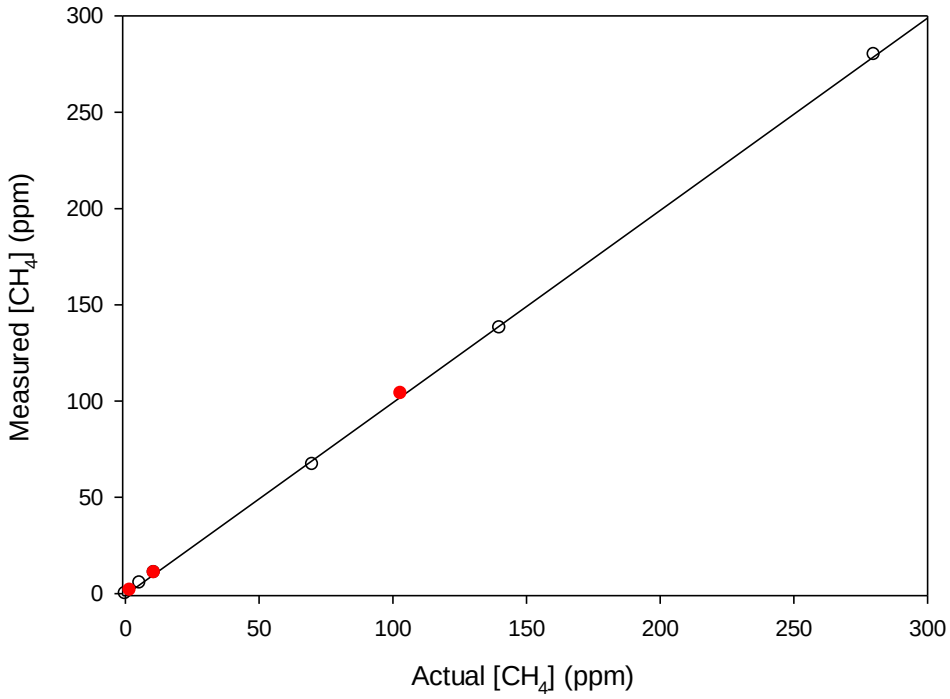

Figure 3.2. Calibration curves obtained for the methane analyser. Open circles correspond to points made using gas mixtures generated with a gas diluter. Red circles represent a multipoint calibration made using reference gases several months later.

The response of the instrument remained linear at least to 280 ppm CH_4. One of the routine multipoint calibration curves using the three reference gases made several months later (red markers) is also plotted to demonstrate the low drift characteristics of the instrument.

Multipoint calibrations were performed before and after each field campaign and single point calibration checks were made periodically in the field.

3.3 Plume Traverses

Methane emissions from well pads were estimated using a plume dispersion method. In this method, the CH_4 concentration profile in a plume originating from CH_4 emission sources on the pad is measured at some distance downwind of the pad by performing traverses across the plume. Since the plume comprises all CH_4 released from the pad, it yields total emissions from each pad. The technique is illustrated in Figure 3.3.

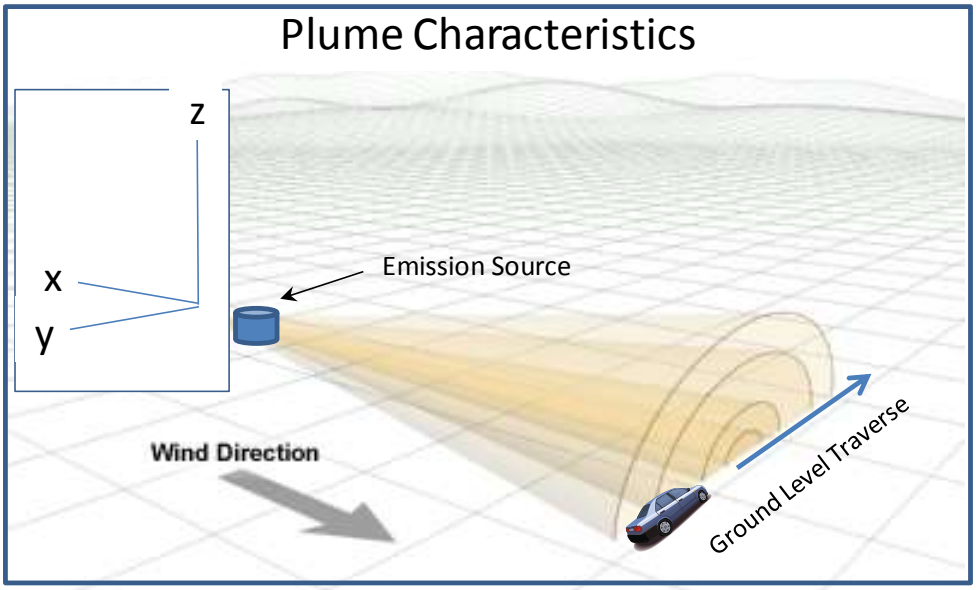

Figure 3.3. Schematic representation of the plume traversing experiments.

The field vehicle with the CH_4 analyser was driven 15 to 50 m downwind of each well to measure the ground level CH_4 concentration across each plume. The emission flux, *F*, over each traverse was estimated by integrating the CH_4 concentration enhancement (i.e. the measured concentration minus background CH_4 concentration), *c*, of the plume in the horizontal and vertical directions and multiplying by the average wind velocity, *u*, measured at each site (Equation 3.1). Background CH_4 concentrations were measured by performing upwind traverses of the well pad.

$$F = u \int_{-y}^{y} \int_{0}^{z} c(y,z)\,dy\,dz \qquad \text{Equation 3.1}$$

Since the traverse measurements were made at ground level only, the vertical extent was estimated by reference to the Pasquill-Gifford curves of σ_z (i.e. the standard deviation of the distribution of CH_4 concentration in the vertical direction) as a function of downwind distance under given atmospheric turbulence conditions (Hanna et al., 1982). The vertical concentration profile of CH_4, within the plume was assumed to decrease from the ground level concentration with height according to a Gaussian distribution across the traverse plane. For each well, an average emission rate was determined from up to 10 traverses made over about a 20-minute period.

One of the primary sources of uncertainty with the plume traversing method is associated with determining the height of the plume because it must be estimated rather than measured. To assess the level of uncertainty in the plume traversing results, we performed a number of experiments where CH_4 was released from a cylinder of compressed gas at a known rate while traverses were made downwind of the source. The results of the traverses were then compared with the actual rate of CH_4 release. These controlled release measurements were made at a site near the CSIRO laboratories in Newcastle where there were no other sources of CH_4 present and to simulate field conditions, traverses were made between 15 and 50 m downwind of the controlled release point. The results of these experiments are discussed in Section 4.1.

3.4 Leak and Vent Testing

At each well site an initial survey for elevated CH_4 concentrations was made by performing vehicle traverses as described above to determine if CH_4 emissions were present. The presence of elevated CH_4 concentrations indicated some type of leak, venting or engine exhaust emission from the pump power pack. Where CH_4 was detected, more detailed examination of the facility was undertaken using a probe connected to the vehicle mounted CH_4 analyser to locate the source or sources of CH_4 (Figure 3.4). On

some occasions, leaks were located by spraying a leak detection solution (Snoop, Swagelok Company) onto individual components.

Figure 3.4. Locating equipment leaks at a CSG well pad.

When the source of the leak was identified, the leak rate was measured. During the first set of field measurements, leak rates were measured in accordance with the USEPA Protocol for Equipment Leak Emission Estimates (USEPA, 1995). In this procedure, the leaking component is enclosed in a plastic bag or sleeve and an air stream is passed through the bag at a known rate while the outlet stream is analysed for CH_4 concentration. Although this is a proven method for quantifying leak rates, it was found to be very slow and labour intensive. For later measurements (and the majority of the results reported here) we constructed a high-flow apparatus, similar in principle to the 'Hi-Flow' device reported by Kirchgessner et al. (1997). In this system, a high capacity fan attached to a 100 mm diameter flexible tube was used to provide an air stream around the leak point to entrain the leaking CH_4. A variable power supply was used to allow the fan speed to be varied up to a maximum flow rate of approximately 80 L s^{-1} (4.8 m^3 min^{-1}).

During leak tests, the inlet of the hose was held within about 150 mm of the apparent leak point while the CH_4 concentration in the outlet air stream was measured with the CH_4 analyser in the field vehicle. The leak rate, R_l, was calculated from the volumetric flow rate of the air stream, V, and the steady state CH_4 concentration, c, according to Equation 3.2

$$R_l = V \times c \qquad \text{Equation 3.2}$$

A schematic diagram of the apparatus is shown in Figure 3.5.

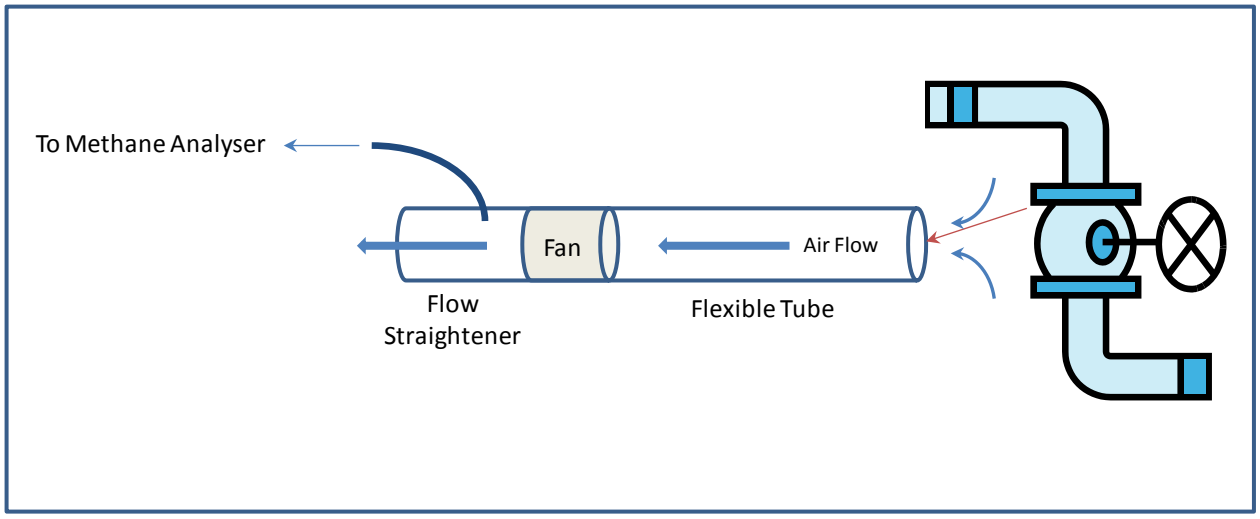

Figure 3.5. Schematic diagram of the leak testing apparatus. Methane leaking from a component (red arrow) is entrained in the airstream drawn into the tube by the fan.

Occasionally emission rates from some sources (e.g. vents and pneumatic devices) were amenable to a simple measurement technique where the exhaust point was sealed in a plastic bag of known volume and measuring the time required to fill the bag. In a few cases where the emission rate was reasonably constant, emission rates were measured by attaching a flow calibrator (DryCal DR2) to the emission outlet.

3.5 Surface Emissions

Measurements were made on the ground surface near well heads to determine if CH_4 was migrating around the outside of well casings or through casing walls. These measurements were made using a surface flux chamber, a technique frequently used to measure emission rates of soil gases. For these measurements, a plastic cylindrical chamber 37.5 cm in diameter and 40 cm high with a total volume of about 45 L and an area of coverage of 0.11 m^2 was placed on the ground at each sampling point. A small solar powered fan mounted in the chamber ensured that the sample within the chamber was well mixed during each experiment. The chamber was connected to the CH_4 analyser in the field vehicle via a ¼" nylon tube and the CH_4 concentration within the chamber, *C*, continuously measured over a period of several minutes. The flow rate of the sample stream from the flux chamber to the analyser was approximately 100 mL min^{-1}.

The CH_4 emission flux, *F*, was calculated according to Equation 3.3

$$F = \frac{dC}{dt} \times \frac{V}{A} \qquad \text{Equation 3.3}$$

where *V* is the volume of the chamber, *dC/dt* is the rate of change in the CH_4 concentration over time, *t*, and *A* is the area of surface covered by the chamber.

A schematic diagram of the chamber system is shown in Figure 3.6

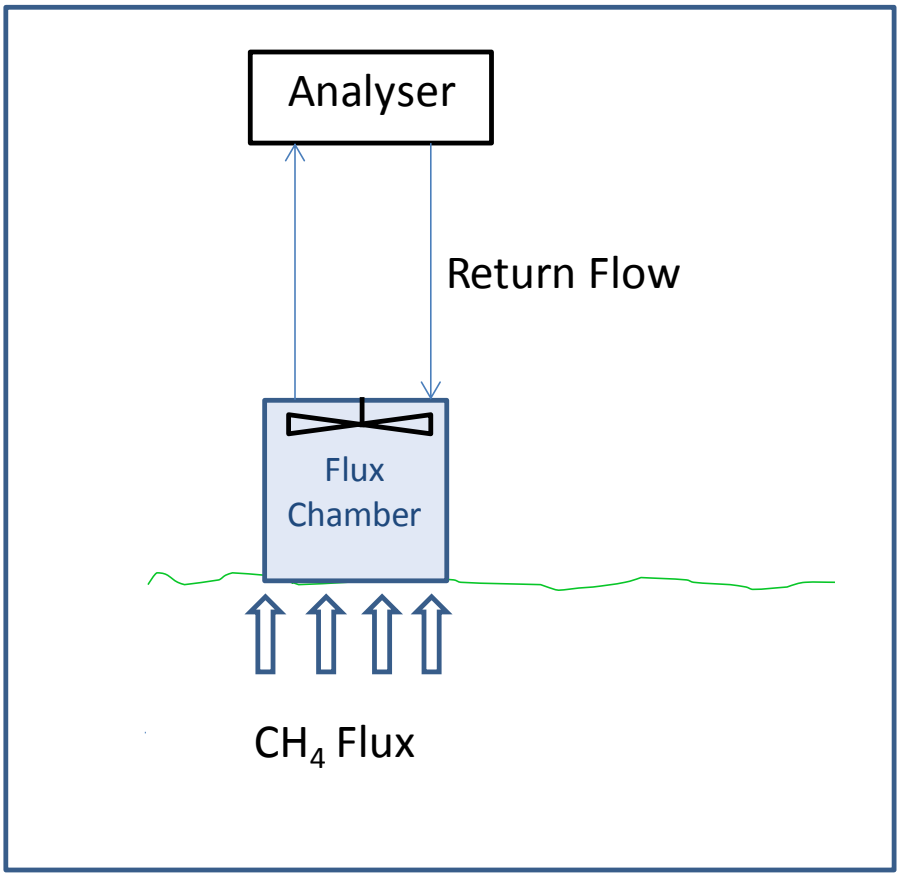

Figure 3.6. Schematic diagram of the flux chamber system used for well casing leak determinations

Typically, chamber measurements were made at four or more points within about 1 m of the well casing. In many cases, the chamber was placed adjacent to the casing, depending on access. Occasionally, additional measurements were made at distances up to about 20 m from the well head.

4 Results

4.1 Controlled Release

Controlled release experiments were conducted on several occasions with CH_4 release rates of between 0.7 and 0.8 g min^{-1} and traversing distances between 15 and 30 m downwind of the release point. Figure 4.1 shows the results of the controlled release experiments. The black markers represent the mean value determined by the traverses while the error bars show the minimum and maximum results determined over each set of traverses. The red markers represent the actual release rate.

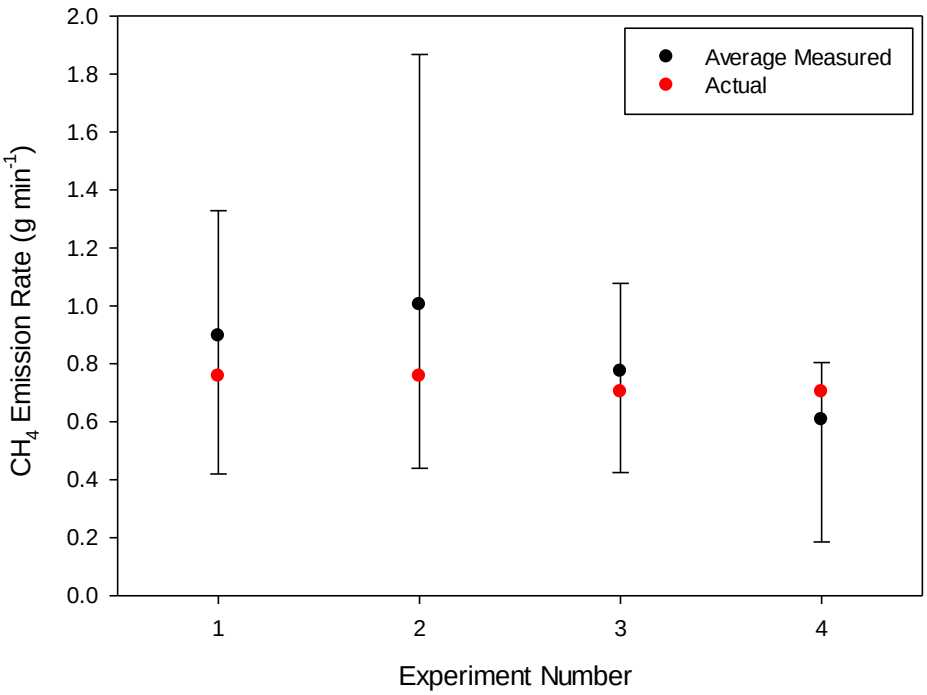

Figure 4.1. Summary of the controlled release experiments showing the CH_4 release rate determined by plume traversing and the actual release rate. Downwind distances were: Exp No 1 = 20 m; Exp No2 = 30 m; Exp No 3 = 15 m; Exp No 4 = 30 m. The error bars represent the range of emission rates measured during each set of six traverses.

Two initial experiments using a higher release rate of approximately 3.5 g min^{-1} and up to 50 m downwind overestimated the actual emission rate by about 100 and 60 % respectively. However, these experiments were based on only two traverses each so the poor agreement is unsurprising. The subsequent experiments (shown in Figure 4.1) were made using six traverses for each determination. In these cases, the agreement was much better with the emission rate determined by the average of the six runs being within about 30 % of the actual release rate, although there was significant variation among the individual traverses as shown by the error bars in Figure 4.1. Measurements made at CSG wells using the plume traversing method were therefore based on at least six and usually 10 or more individual traverses at each site.

4.2 Well Measurements

Emission measurements were made at 43 sites in NSW (six sites) and Queensland (37 sites). Most sites had only a single well on the pad, but there were a number where up to four well heads were located on an individual pad. The majority of wells were production wells, although 11 were not flowing at the time of the

measurements due to maintenance or other activities. Two of the wells examined were plugged and abandoned and one well had been 'suspended' where the well head was still in place but had been disconnected from the gathering network and most of the surface equipment had been removed.

Twenty-nine wells were producing gas during the measurements, flowing at rates ranging from less than 1000 m^3 day^{-1} to more than 186,000 m^3 day^{-1}. Eleven of the sampled wells were hydraulically fractured. The selection also included a mix of free-flowing wells (water was not pumped from the well) and pumped wells (water was pumped from the well to allow gas flow). Pumped wells used on-site engines to power hydraulic pumps or generators to drive down-hole water pumps. In all but one case (which used diesel), these engines were fuelled from gas supplied from the well. A summary of the wells is shown in Table 4.1. To maintain commercial confidentiality, the well locations and operators of individual wells are not identified in this report.

Table 4.1. Details of wells examined during this study.

Well Number	Completion Date	Production Rate (m^3 day^{-1})	Fracture Stimulated	Type	Pump with Engine	Wells on Pad
A1	11/10/1999	1,470	Yes	Vertical	No	1
A2 - Suspended	1/05/2003	0	Yes	Vertical	No	1
A3	1/07/2007	0	Yes	Vertical	Yes – not running	1
A4	20/04/2010	18,400 (total of all 4 wells on pad)	No	Horizontal	No	4
A5	8/06/2011	14,900	No	Horizontal	Yes	2
A6	11/12/2007	13,700	No	Horizontal	No	1
B1	24/09/2006	38,880	No	Vertical	Yes	1
B2	11/01/2008	0	No	Vertical	No	1
B3	06/08/2011	9,360	No	Vertical	Yes – not running	1
B4	21/09/2010	26,400	No	Vertical	Yes – not running	1
B5	08/12/2010	0	No	Vertical	No	1
B6	27/04/2003	23,760	Yes	Vertical	Yes	1
B7	09/08/2007	26,400	No	Vertical	Yes	1
B8	26/01/2008	62,400	No	Vertical	No	1
B9	23/06/2008	7,680	No	Vertical	Yes	1
B10	07/04/2007	55,200	No	Vertical	No	1
B11	23/06/2011	94,602	No	Vertical	Yes – not running	1
B12	28/06/2011	0	No	Vertical	Yes – not running	1
B13	21/02/2005	0	No	Vertical	No	1
B14	30/08/2007	75,360	No	Vertical	No	1

B15	08/04/2009	70,800	No	Vertical	No	1
C1	15/05/2001	76,101	No	Vertical	Yes	1
C2	2/08/2003	853	No	Vertical	Yes	1
C3	4/10/2007	0	No	Vertical	Yes – not running	1
C4	29/03/2007	52,458	No	Vertical	Yes	1
C5	29/03/2007	58,594	No	Vertical	Yes – not running	1
C6	28/01/2008	186,464	No	Vertical	Yes	1
C7	17/09/2009	0	Yes	Vertical	No	1
C8	22/05/2010	0	No	Horizontal	No	2
C9	16/10/2003	78,731	Yes	Vertical	No	1
C10	1/10/2003	85,556	Yes	Vertical	No	1
C11	27/08/2004	0	Yes	Vertical	No	1
D1 - Abandoned	8/11/2003	0	No	vertical	No	1
D2	1/09/2005	93,400	Yes	vertical	No	1
D3 - Abandoned	29/11/2003	0	Yes	vertical	No	1
D4	19/04/2004	0	Yes	vertical	Yes (x2 – not running)	1
D5	7/11/2009	7,900	No	vertical	Yes (x2)	1
D6	28/11/2009	0	No	vertical	Yes (x2)	1
E1	16/3/2008	43,843 (total of both wells on pad)	No	vertical	Yes	2
E2	7/9/2008	26,847	No	vertical	Yes	1
E3	16/3/2007	3,707	No	vertical	Yes – not running	2
E4	31/5/2009	6,598	No	vertical	Yes	1
E5	31/5/2005	14,498 (total of all 3 wells on pad)	No	vertical	Yes	3

Downwind plume traverses were made at all wells sites except Wells B7 and C3 where the wind was too light to produce stable plumes. Of the well sites where traverses were made only three did not exhibit any CH_4 emissions. These were the two plugged and abandoned wells (D1 and D3) and the suspended well (A2). All of the other wells examined exhibited some level of CH_4 emissions although in most cases the amount was relatively small. The plume traversing results for all wells are presented in Table A1 in the Appendix.

On-pad measurements were made at most wells except in a few cases where high ambient CH_4 levels from major leaks or vents made locating minor leak points difficult. In one case at Well B2, CH_4 released from a vent on a water gathering line was drifting over the pad components so it was not possible to determine if

there were other leaks against the high background. Similar conditions were encountered at Wells C3 and E4 where variable plumes from leaks around the water pump shaft seals precluded reliable leak detection. In one case we attempted to measure emissions from a well about 500 m downwind of a gas compression plant but the CH_4 emissions from the plant prevented any measurements being made at this site.

Most of the CH_4 emissions were found to be derived from equipment leaks and venting but we also found that exhaust from the engines used to drive the water pumps on some wells was frequently a significant source of methane. Fifteen of the pumped wells had the engines operating during the measurements and in most cases the exhaust was found to contain CH_4 that contributed to total emissions. In a few cases, the plume from the engine exhaust was sufficiently spatially separated from other sources of CH_4 to quantify the sources separately using the traverse method (Figure 4.2).

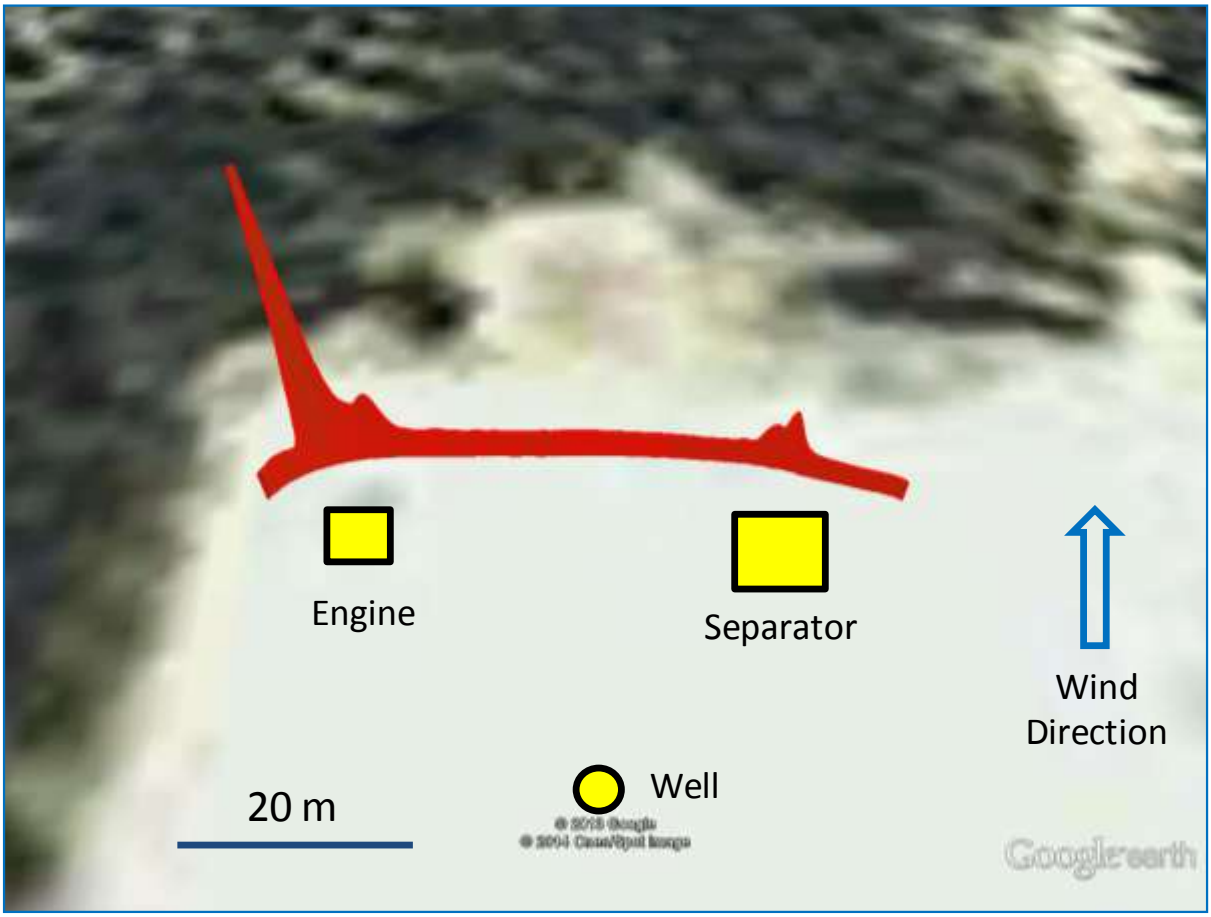

Figure 4.2. Methane concentration profile at Well C2 showing the separate plumes associated with the engine and equipment leaks elsewhere on the pad.

However, in most cases the plumes were coincident and the exhaust component could not be separated. To attempt to estimate the magnitude of engine emissions, we measured the CH_4 concentration in the exhaust outlet of the engine where this was possible. The range of CH_4 concentration varied considerably; from only a few ppm to more than 1500 ppm. The exhaust gas flow rate was estimated from the nominal fuel consumption (often stated on the engine nameplate) or power rating and assuming a 33 % efficiency and 17:1 air fuel ratio.

In the example for Well C2 shown in Figure 4.2, the plume traverse yielded an emission rate from the engine of 0.8 g min^{-1} compared to the estimate based on the fuel consumption and exhaust CH_4 concentration of 0.9 g min^{-1}. In another example, engine emissions from Well B7 were estimated using the exhaust method to be 0.2 g min^{-1}. A separate measurement made by the well operator using a stack testing method also gave 0.2 g min^{-1}. While these two examples suggest that this method provides a reasonable approximation of exhaust CH_4 emissions, in many cases the CH_4 concentration measured was well above

the calibrated range of the CH_4 analyser (i.e. > 280 ppm) and hence the results can only be considered indicative.

Although on-pad measurements provided reasonably accurate leak rate results for individual leak points, the large number of possible emission sources including equipment leaks, vents, pneumatic devices and engine exhaust presented a risk that some emission points on each pad would be missed during the surveys (Figure 4.3).

Figure 4.3. CSG well pad showing some of the surface equipment and potential emission points. Note the engine in the background for supplying hydraulic power to the water pump.

To check this we compared the emission rates determined from the on-pad measurements to those calculated from the downwind traverses, which capture all emissions from the pad. Ideally therefore, if all the emission sources have been accounted for, on-pad measurements should equal emission rates determined from traverse data. Apart from one result, there was generally good agreement between the two methods, which is shown in Figure 4.4 where the emission rate determined for each well by the on-pad methods is plotted as a function of the traversing results. The outlier (red marker in Figure 4.4) corresponds to Well B2 where the traverses were made under very light and variable conditions, which make accurate quantification difficult. The mean traverse result for this well was approximately 17 g min^{-1} but this result exhibited the greatest variably of all the traverses, ranging from 1 to 66 g min^{-1}. If this result is omitted from the plot, the slope of the line is close to 1 (0.94) confirming that the on-pad measurements generally accounted for the main emission points i.e. there were no major sources that were missed during the leaks surveys.

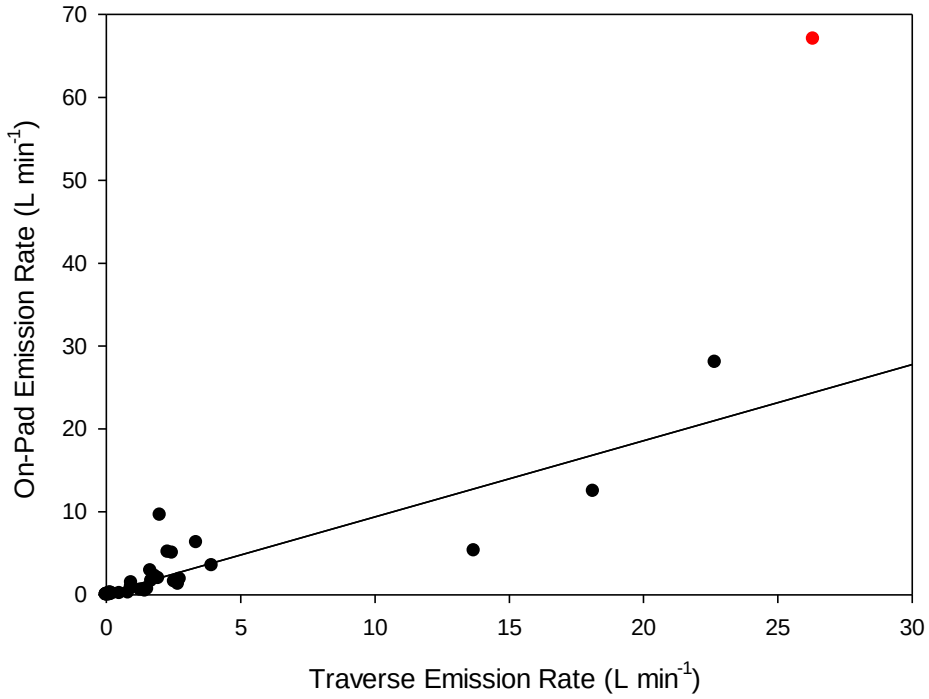

Figure 4.4. Correlation of total CH_4 emissions determined by traverses with on-pad measurements

The well site results from individual companies are discussed in more detail in the following sections.

4.2.1 COMPANY A

Figure 4.5 summarises the total emissions measured at Company A's well sites using the traversing method. At the time of the measurements only four wells were producing gas – Well A2 was suspended and Well A3 was shut-in for maintenance.

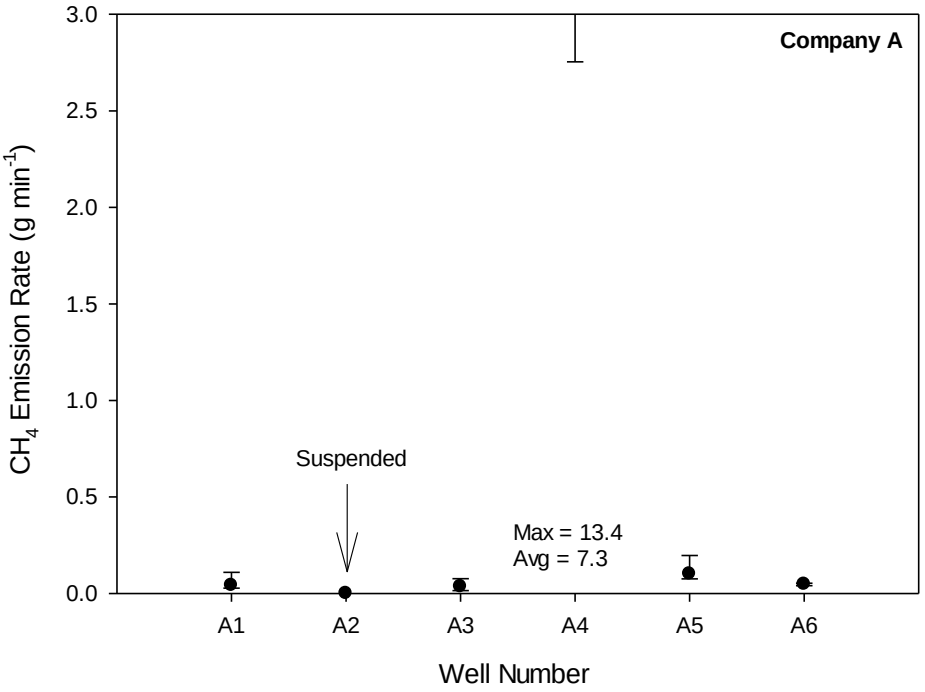

Figure 4.5. Total CH_4 emission rates estimated at Company A's well sites using the traversing method.

Apart from the suspended well (A2) emissions were detected at each site. Generally emissions were very low rwith five of the wells having emissions below about 0.1 g min^{-1}. On-pad measurements made at the well sites showed that in two cases (Wells A1 and A5) the emissions were due to the operation of pneumatic devices with emission rates of ~75 mg min^{-1} and 55 mg min^{-1}, respectively.

Two other wells (A3 and A6) were also found to have minor emissions but at the time the measurements were made, venting from pneumatic equipment was not contributing (i.e. these devices did not operate over the few hours we were on site at each well). In the case of A6, CH_4 was leaking slowly from a loose plug on a branch pipe at a rate of 22 mg min^{-1}. This leak was repaired by gas company personnel shortly after it was identified and further measurements on site showed that the leak had been eliminated. At Well A3, a leak was found in the gathering line, but again, this was very small amounting to less than 1 mg min^{-1}.

The largest emissions were found at Well A4. Two separate sets of traverses yielded an average emission rate of 7.3 g min^{-1}. Methane leaks were detected at a valve and pipe joint on the well pad but the combined emission rate from these was about 7 mg min^{-1} so the bulk of the methane release was from another source. This well was on a pad with three other wells within close proximity, which were not examined in detail during this campaign, so it is possible that some of the observed methane in the plume may have originated from these other wells. However, the bulk of the source was traced to a buried gathering line adjacent to the pad that serviced all four wells. We attempted to measure the emission rate using the surface flux chamber method; however, because of the diffuse nature of the emissions through the gravel, this was not successful.

Although the average emission rate of 7.3 g min^{-1} (15.5 m^3 day^{-1} at 15 °C) determined by the traverses was by far the largest emission source found at Company A, it represented only about 0.1 % of the indicated gas flow of 18,400 m^3 day^{-1} from the four wells on the pad.

A summary of the emissions determined by on-pad measurements at Company A is provided in Table 4.2.

Table 4.2. Summary of on-pad emission rates measured at Company A sites; nf denotes 'not found'. Note the leak rate shown for Well A6 was determined from the traverses.

Well Number	Leaks (g min^{-1})	Vents (g min^{-1})	Pneumatics (g min^{-1})
A1	3.3×10^{-4}	nf	7.5×10^{-2}
A2	0	nf	nf
A3	4.5×10^{-4}	nf	nf
A4	7.3	nf	nf
A5	0	nf	5.5×10^{-2}
A6	2.2×10^{-2}	nf	nf

4.2.2 COMPANY B

Methane emissions estimates based on the traverses for the Company B wells are summarised in Figure 4.6.

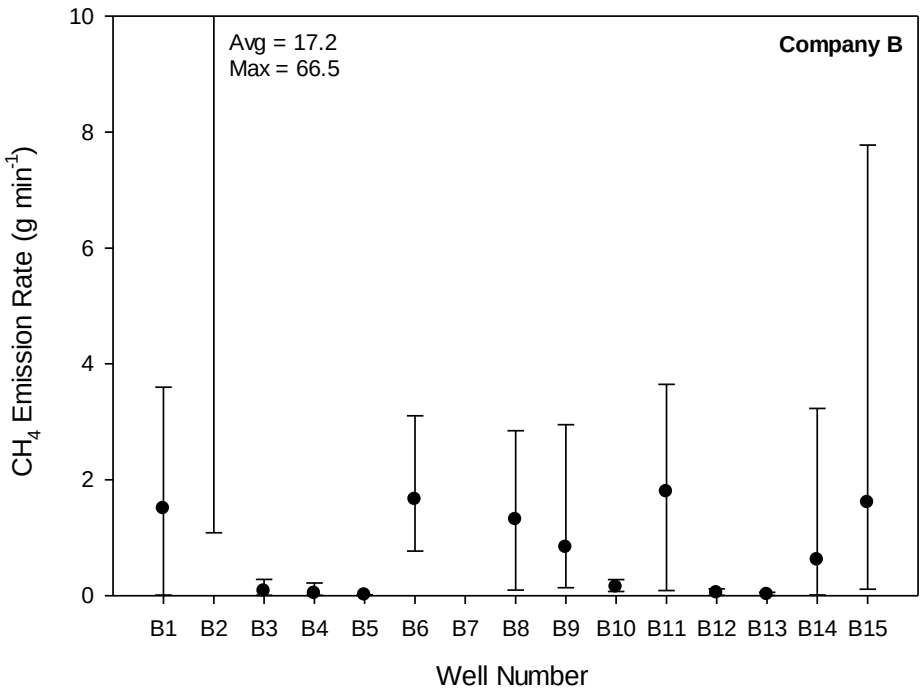

Figure 4.6. Total CH_4 emission rates estimated at Company B's well sites using the traversing method.

These emissions were somewhat higher than measured at Company A with average emissions ranging from less than 50 mg min^{-1}, (B4, B5, B12 and B13) to 17 g min^{-1} (B2). Note however, that one individual traverse on B2 indicated an emission rate of more than 66 g min^{-1}. The traverses at Well B2 were made under light and variable wind conditions so the results are subject to high uncertainty. More accurate emissions measurements of emissions were made at B2 using an on-pad method. In this case, CH_4 was found to be predominantly released from a single vent on a water gathering pipe from the well. The flow rate from the vent was relatively constant at 44 g min^{-1} (measured using a flow calibrator), which was within the range of the traverses but higher than the traverse average of 17 g min^{-1}. The high CH_4 emission rate however,

meant that it was not possible to identify any other sources on the pad because the plume was engulfing the surface equipment.

Well B2 was not flowing at the time of the measurements, but assuming the normal flow rate is 26,400 m^3 day^{-1} (i.e. the median production rate of the Company B wells examined), fugitive emissions from this vent represent about 0.4 % of the well's production.

Emissions at the other Company B well sites were much lower than B2, with emission rates generally less than 2 g min^{-1}. Most of the well sites exhibited a small level of leakage from certain items of equipment and especially a particular brand of pressure regulator. These regulator leaks however, were quite low with the maximum measured less than 25 mg min^{-1}. Most of the CH_4 emissions were, like Well B2, from vents present on many of this company's wells. Vent emissions were significantly higher than the equipment leaks, typically more than 1 g min^{-1}, with the maximum of 44 g min^{-1}.

The on-pad measurements for Company B are summarised in Table 4.3.

Table 4.3.Summary of on-pad emission rates measured at Company B sites; nf denotes 'not found'.

Well Number	Leaks (g min^{-1})	Vents (g min^{-1})	Pneumatics (g min^{-1})
B1	2.4×10^{-3}	2.9	nf
B2	nf	43.8	nf
B3	2.1×10^{-4}	nf	nf
B4	1.5×10^{-3}	nf	nf
B5	nf	nf	nf
B6	6.4×10^{-3}	1.0	nf
B7	9.6×10^{-4}	1.1	nf
B8	2.1×10^{-2}	6.2	nf
B9	2.4×10^{-3}	nf	nf
B10	2.3×10^{-2}	3.6×10^{-2}	nf
B11	2.5×10^{-2}	1.2	nf
B12	3.0×10^{-4}		nf
B13	1.0×10^{-3}	$< 10^{-4}$	nf
B14	3.94×10^{-3}	0.9	nf
B15	2.4×10^{-3}	3.3	nf

In addition to the emissions from the well pads, we found a significant CH_4 emission point from a water gathering line installation near Well B13 (Figure 4.7).

Figure 4.7. Methane emission sources on a water gathering line.

Methane was being released from the two vents shown in Figure 4.7 at a rate sufficient to be audible a considerable distance from the vents. It was not possible at the time to the site visit to directly measure the emission rate from the vents due to restricted access, however, the CH_4 concentration 3 m downwind of the vents was 15 % of the lower explosive limit of CH_4 (i.e. 7,500 ppm). Based on the prevailing wind speed, we estimate that the CH_4 emission rate from the two vents was at least 200 L min^{-1} (130 g min^{-1}) or almost 300 m^3 day^{-1}. This is a factor of three more than the highest emitting well examined during this study.

4.2.3 COMPANY C

Figure 4.8 summarises the CH_4 emission rates estimated by the traversing method for Company C. Emissions were generally estimated to be below 1.5 g min^{-1}, except for Wells C1 and C4, with emission rates of about 8.7 and 11.8 g min^{-1}, respectively. The bulk of the emissions from wells C1 and C4 were due to CH_4 in the engine exhaust rather than venting or equipment leaks. Similarly, emissions from Wells C2 and C6 comprised mainly CH_4 in engine exhaust although the emissions rates were much lower than C1 and C4. On-pad measurements at each of the wells showed that emissions from the wells were generally relatively low when the engine exhaust is excluded (Table 4.4). In this case, leaks were mostly less than 0.3 g min^{-1}. Most of these leaks were found to be from vent pipes on equipment such as pressure relief valves or pressure regulators similar to those on Company B's well sites. In one case (Well C10), a pneumatic device was found to be venting at an average rate of 0.5 g min^{-1} in addition to the equipment leak rate of 0.3 g min^{-1} to give a total emission of 0.8 g min^{-1}.

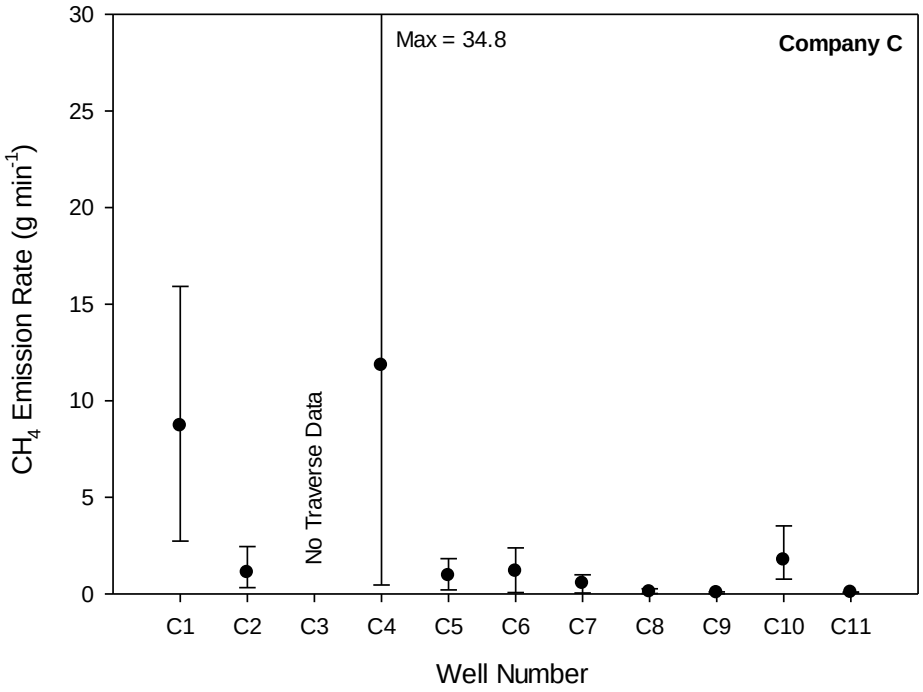

Figure 4.8. Total CH_4 emission rates estimated at Company C's well sites using the traversing method.

Traverses were not made at Well C3 due to lack of wind, however, on-pad inspections revealed a significant gas leak was on the seal of the water pump shaft. The emission rate from this leak was approximately 28 g min^{-1} (measured using the high-flow apparatus), which was the second largest well emission (after B2) and the largest equipment leak of the 43 sites examined. Since this well was shut-in at the time of measurement, it was not flowing but using the median flow rate of Company C's wells (52,500 m^3 day^{-1}) the leak rate corresponds to about 0.1 % of the well's production.

The water pump shaft seal was also found to be the source of CH_4 leakage at Well C5 but in that case, the emission rate was about 0.3 g min^{-1}, about 100 times less than C3.

Table 4.4. Summary of on-pad emission rates measured at Company C sites; nf denotes 'not found'.

Well Number	Leaks (g min^{-1})	Vents (g min^{-1})	Pneumatics (g min^{-1})
C1	5.3×10^{-2}	nf	nf
C2	0.2	nf	nf
C3	28.	nf	nf
C4	8.0×10^{-2}	nf	nf
C5	0.3	nf	nf
C6	0.2	nf	nf
C7	0.1	nf	nf
C8	2.1×10^{-3}	nf	nf
C9	8.9×10^{-3}	nf	nf

C10	0.3	nf	0.5
C11	7.4×10^{-2}	nf	nf

4.2.4 COMPANY D

Two of the wells at Company D were plugged and abandoned with all surface equipment removed. Detailed traverses and flux chamber measurements made on the well sites revealed no sign of any residual emissions from these wells. The traversing results for Company D are shown in Figure 5.9.

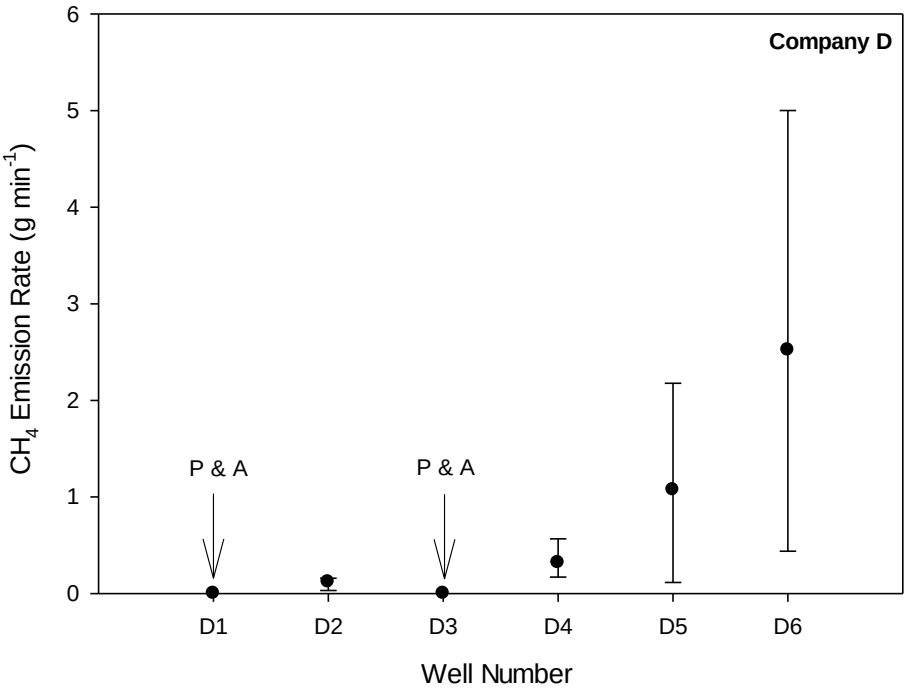

Figure 4.9. Total CH_4 emission rates estimated at Company D's well sites using the traversing method.

Of the operating wells, D2 had the lowest emissions with on-pad measurements indicating total emissions of less than 60 mg min^{-1}, which were due to minor equipment leaks. Well D4 also had low emissions totalling about 65 mg min^{-1}. A small emission from a pneumatic actuator of approximately 14 mg min^{-1} was also found on well D4.

Wells D5 and D6 had higher total CH_4 emission rates and although affected by engine exhaust, significant proportions of the observed emissions were due to equipment leaks. In the case of D5, most of the CH_4 was leaking from the water pump shaft seal at about 1.5 g min^{-1} (Table 5.5). For D6, we estimate that about two thirds of the CH_4 was due to engine exhaust but approximately 0.75 g min^{-1} was leaking from what appeared to be a damaged diaphragm in a valve actuator (Figure 5.10). Several smaller leaks on this well resulted in a total leak rate of about 0.9 g min^{-1}.

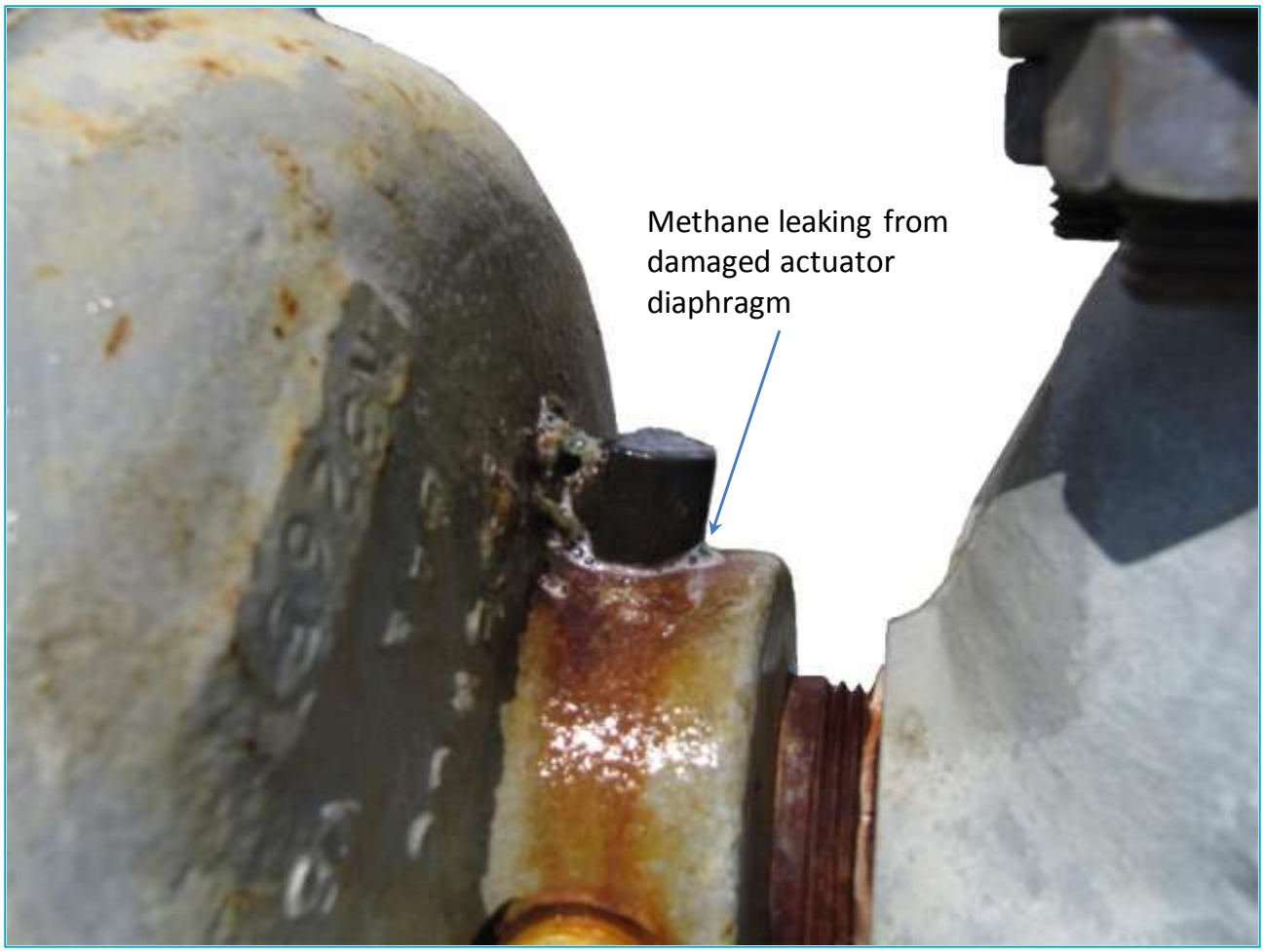

Figure 4.10. Methane leak from a valve actuator. Note the soap solution bubbles around the emission point.

Table 4.5 shows a summary of the on-pad results from Company D.

Table 4.5. Summary of on-pad emission rates measured at Company D sites; nf denotes 'not found'.

Well Number	Leaks (g min^{-1})	Vents (g min^{-1})	Pneumatics (g min^{-1})
D1	0	nf	nf
D2	5.7×10^{-2}	nf	nf
D3	0	nf	nf
D4	6.4×10^{-2}	nf	1.4×10^{-2}
D5	1.5	nf	nf
D6	0.9	nf	See note

Note: Although the emissions from the actuator shown in Figure 4.10 were from a pneumatic device, it appeared that this was due to a leak rather than normal operational emissions. Hence we have classified this as a leak in Table 4.5

4.2.5 COMPANY E

The traverse results obtained for Company E are shown in Figure 4.11. The lowest emitting well of the five examined was E5. This well was located on a pad of three wells, with a single engine providing power to all three water pumps. Emissions from all three wells were less than 60 mg min^{-1}, most of which were

probably associated with engine exhaust. We did not find any equipment leaks or venting emissions at this site.

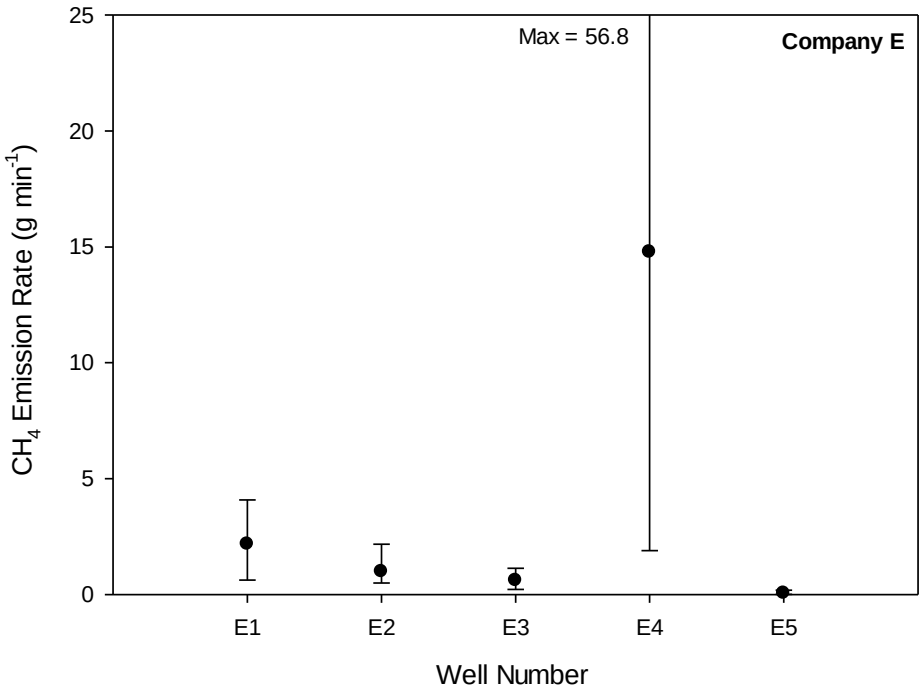

Figure 4.11. . Total CH_4 emission rates estimated at Company E's well sites using the traversing method.

The other wells, however, showed higher emissions, the largest of which was on Well E4 with an emission rate of about 15 g min^{-1}. This was traced to a leak on the water pump shaft seal. Like a number of other well sites examined during this study, the seal was repaired on site once the leak had been identified and subsequent measurements confirmed that CH_4 leakage was completely eliminated.

Well site E1 was also found to be leaking CH_4 from the water pump shaft seal. This site had two wells on the pad and both were found to be leaking from the seal. The combined rate of leak from this source was 0.7 g min^{-1}. These wells also showed significant leakage from two pressure regulators, similar to those used at various other well pads examined, with a combined emission rate of 1.7 g min^{-1}. Total emissions from leaks at E1 were 2.5 g min^{-1} (Table 4.6).

The next highest emitting well from Company E was E2 but most of these emissions were apparently from the engine exhaust. For E3, a very slight leak was detected from the pump shaft seal (about 40 mg min^{-1}) but most of the CH_4 emissions were from a leak in a filter attached to the engine fuel line (0.6 g min^{-1}).

Table 4.6. Summary of on-pad emission rates measured at Company E sites; nf denotes 'not found'.

Well Number	Leaks (g min^{-1})	Vents (g min^{-1})	Pneumatics (g min^{-1})
E1	2.5	nf	nf
E2	nf	nf	nf
E3	0.6	nf	nf
E4	15	nf	nf
E5	0	nf	nf

4.3 Casing Leaks

CSG wells are designed so that gas is extracted from the seam through a well casing but if the casing is damaged or improperly sealed into the surrounding strata, it is possible that gas can migrate to the surface outside the casing (Figure 4.12). To determine if CH_4 was escaping from the well casing, the flux chamber method was applied at each well site to measure the emission rate of any leakage from around the outside of the casing.

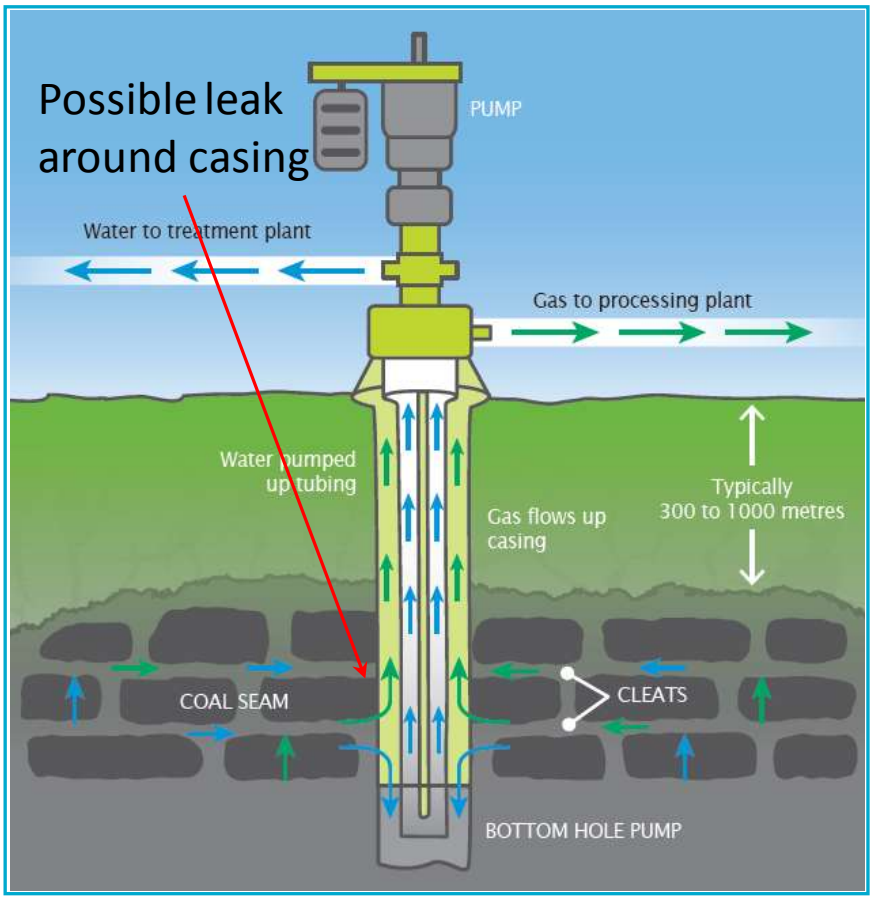

Figure 4.12. Schematic representation of a CSG well showing a possible route for CH_4 leaking outside a casing.

We anticipated that leakage from this source may be quite low, so it was important to ensure that the measurement technique had sufficient sensitivity to detect low level seepage. Therefore, prior to making field measurements a series of preliminary experiments were performed to determine the lower limit of detection of the method. Several experiments were made using a controlled release of CH_4 into the flux chamber system. Figure 4.13 (a) shows a plot of the CH_4 concentration within the chamber over about 5 minutes. The actual flow rate of CH_4 into the chamber was 7.76×10^{-5} g min^{-1} whereas the measured rate was 7.42×10^{-5} L min^{-1} or a difference of about 4 %. While this is a very low emission rate (cf. the smallest well leak rates of ~3×10^{-4} g min^{-1}) the ultimate sensitivity was several orders of magnitude lower. Measurement of CH_4 emissions from natural surfaces showed that emission rates less than 1×10^{-7} g min^{-1} could be reliably quantified (Figure 4.13 b).

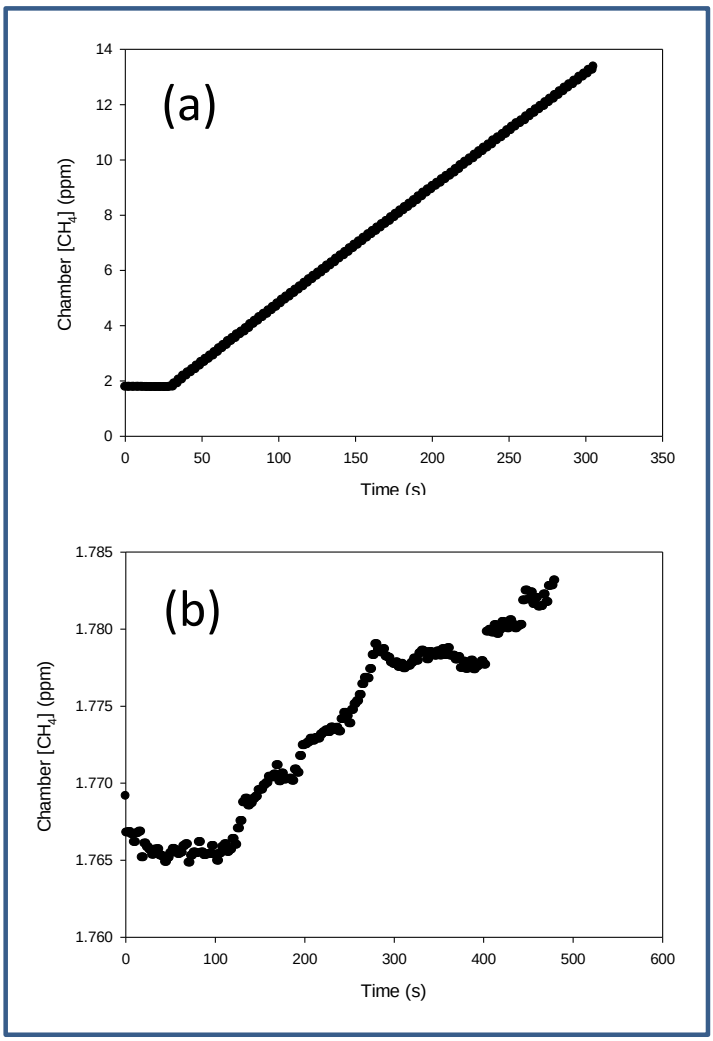

Figure 4.13. Methane concentration as a function of time in the flux chambers (a) controlled release experiment; (b) natural surface emission.

At the well sites, even with the very high sensitivity of the chamber method, we did not detect any emissions from around the well casing. Because the flux chamber measurements were applied at discreet points around the well it is possible that leak points were missed, however we believe that this was very unlikely since any significant emissions would have been detected during the mobile plume traverses and leak detection measurements made near the well heads.

5 Discussion

Overall, the emission rates measured at the well sites were quite low, especially when compared to the volume of gas produced. Of the 43 sites examined, 19 had emission rates less than 0.5 g min^{-1} and 37 less than 3 g min^{-1}; however, there were a number of wells with substantially higher emission rates up to 44 g min^{-1} (Figure 5.1).

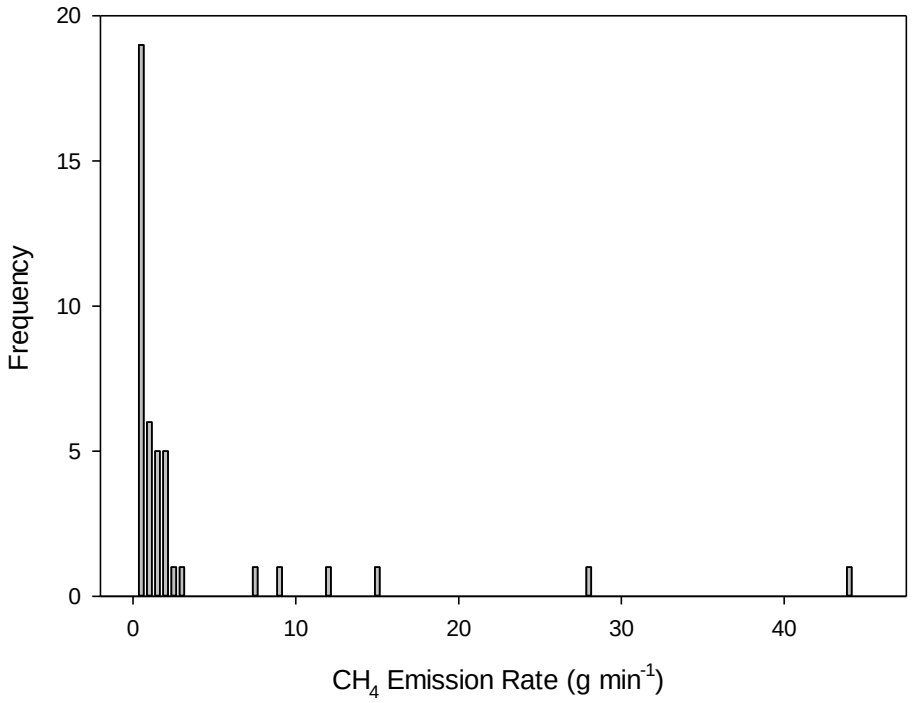

Figure 5.1. Histogram of emission rates from all sources measured at the 43 well sites.

Well pad emissions were found to be derived from several sources:

- exhaust from engines used to power dewatering pumps,
- vents and the operation of pneumatic devices and
- equipment leaks.

The mean emission rate of all of these sources for all wells is 3.2 g min^{-1} whereas the median (middle value) is 0.6 g min^{-1}.

Engine exhaust is not considered to be a fugitive emission for the purposes of greenhouse accounting since it is counted separately as a combustion source. Nevertheless, exhaust represented a significant proportion of the total CH_4 emissions at some well sites. The wide range of CH_4 concentrations present in the exhaust meant that the contribution of exhaust to overall emissions was highly variable. Some engines appear to have very low CH_4 emissions such as that at Well A5. Similarly, an unidentified well in Queensland was found to have no detectable CH_4 in the exhaust within close proximity to the pad (Day et al., 2013). On the other hand, engine exhaust was by far the primary source of CH_4 emissions at some wells (e.g. Wells C1 and C4).

As noted in Section 2, methane emissions from combustion are estimated for NGER reporting using an emission factor of 0.1 kg CO_2-e GJ^{-1} (DIICCSRTE, 2013b), which is equivalent to 4.8 g CH_4 GJ^{-1} using a global warming potential for CH_4 of 21. Assuming that the fuel consumption of the well site engines was 594 MJ

h^{-1} (indicated on the nameplate fitted to one make of engine commonly used throughout the industry), this equates to a CH_4 emission rate of 0.05 g min^{-1}, which lower than some of the estimates made during the study. Well C4 for example was estimated to be emitting CH_4 at a rate of 11.8 g min^{-1}.

Pneumatic devices, which are potential emission points, were installed at many wells, although during the measurement campaign, only seven of these were releasing CH_4 at the time of the site visits. Emissions from the these pneumatic devices ranged from 3.8×10^{-2} to 0.47 g min^{-1} with a mean emission rate 0.12 g min^{-1} and standard deviation of 0.18 g min^{-1}. This is somewhat lower than the emission rate for pneumatic devices recently reported by Allen et al. (2013). They found that the average emission rate from intermittent pneumatic devices at U.S. unconventional gas well was 5.9 ± 2.4 g min^{-1}. The result obtained for the Australian CSG wells is also lower than the production average emission factor for pneumatic devices provided in the API Compendium (API, 2009) of 345 ± 49.5 scf d^{-1} (4.6 ± 0.66 g min^{-1}).

It is not clear why these emission rates are lower than the U.S. estimates; however, it should be borne in mind that the results of our study represent only a very small sample. The Allen et al. (2013) study examined 305 devices compared to only seven in our study. Another reason for the difference may be due to the intermittent operation of the devices. Most of the CH_4 emission apparently occurs when the devices operate and hence the frequency of operation has a strong influence on the emission rate so a longer period of sampling may have yielded different results.

Despite the uncertainty of the results for pneumatic devices, it is probable that emissions from these systems will tend to decrease in the future. Some Australian CSG companies are now installing compressed air operated or electrical actuators on newer well pads which will eliminate pneumatic CH_4 emissions from these pads.

Vents installed at various points on some well pad equipment were frequently found to be sources of CH_4 emissions. Of the 43 well sites examined, ten had vents, all from Company B, that were emitting CH_4 at the time measurements were made. The rate of emissions varied substantially from less than 10^{-4} g min^{-1} up to 44 g min^{-1}, which was the highest rate of emissions measured from any source measured during this project. The mean vent emission rate was 6.1 g min^{-1} with a standard deviation of 13.4 g min^{-1}, reflecting the large range of values.

The third main source of well pad CH_4 emissions was from equipment leaks. Most of the wells examined were found to have some degree of leakage from equipment on the pad. Minor leaks (usually less than 60 mg min^{-1}) were found on various items such as fuel lines to engines, valves, sight gauges on separators and other equipment. However, there were some leak points that were consistently found across the well sites. The first of these was a particular type of pressure regulator installed at many wells (Figure 5.2). This device was apparently associated with the separator and was usually found to be leaking a small amount of CH_4. Mostly, these leaks were less than 150 mg min^{-1} but in one case (Well E1) the emission rate was about 1.5 g min^{-1}.

Figure 5.2. Pressure regular that was a common source of CH_4 leakage.

The other common leak point was the seal around water pump shafts on pumped wells (Figure 5.3). The two largest equipment leaks detected were due to leaking seals at Wells C3 and E4. At the time of the site visit, Well C3 was shut-in for maintenance and as a result the pressure on the seal was almost 2 MPa, which was much higher than normal operating pressure and this is likely to have contributed to the high leak rate from the well. This is consistent with a study of leaking wells in Queensland made in 2010 where high CH_4 concentrations (up to 6 % CH_4) due to leaks were often found on shut-in wells that were under high pressure (DEEDI, 2010).

Figure 5.3. Well head showing the location of the water pump shaft and seal which was found to be a common leak point.

At Well E4, the seal had apparently 'dried out' since the previous inspection and was allowing CH_4 to leak around the rotating pump shaft at almost 15 g min^{-1}. After the leak was identified, however, maintenance staff applied more grease to the seal and tightened the gland around the shaft, which effectively eliminated the leak. A smaller leak of around 1.5 g min^{-1} on the shaft seal on Well D5 was also repaired on site by simply tightening the gland.

Although the water pump shaft seal is a potentially large source of CH_4 emissions, it is clear that in many cases these leaks can be easily repaired. Regular inspection of these seals, especially during shut-ins when the well pressure may increase substantially, is therefore likely to be important for minimising well site emissions.

None of the wells examined during this study exhibited any sign of CH_4 emissions around the well casing so this does not appear to be a common route for CH_4 release. Methane leaks have been detected at ground level adjacent to well casings on Australian CSG wells previously but these were traced to leaks in the threaded connection between the casing and well head base (DEEDI, 2010) rather than gas leaking around the outside of the casing.

Despite this, it has been suggested that 6 to 7 % of well completions in the United States are subject to integrity failure that could lead to CH_4 leakage (Ingraffea, 2013). Given that we surveyed less than 1 % of

Australian CSG wells, it is possible that the small sample size is not sufficiently representative to assess the true extent of well leakage. Further work would be required to conclusively determine the extent of casing leaks.

Four of the wells surveyed were horizontal; the remainder were vertical. The range of emissions from the four horizontal wells was 0.05 to 7.3 g min^{-1} compared to 0 to 44 g min^{-1} for the vertical wells. It is not possible based on only four wells to determine if horizontal wells have different emission characteristics compared to vertical; however, it seems unlikely that this would be the case. The emission routes were always associated with surface equipment, some of which was common to both horizontal and vertical well pads.

Eleven wells examined had been hydraulically fractured and as shown in Table 5.1, average emissions from these wells were lower (0.42 g min^{-1}) than those measured on the unfractured wells (4.2 g min^{-1}). Because the data are heavily skewed and it is unlikely that the sample size is statistically representative, it is misleading to draw conclusions about the relative emission rates based on a comparison of means alone. Methane emissions were observed from both fracture stimulated and unfractured wells but in all cases, emissions were from surface equipment that would not be expected to be affected by the stimulation method. Therefore, the observed difference between the emission rates of the fractured and unfractured wells in this sample is probably unrelated to the stimulation method.

Table 5.1. Comparison of emission rates measured on hydraulically fractured and unfractured wells.

	Fractured	Unfractured
Number of Wells	11	32
Mean (g min^{-1})	0.42	4.2
Median (g min^{-1})	0.07	1.0
Std Deviation (g min^{-1})	0.66	14.3

Another parameter that was initially thought to possibly contribute to differences in emission rates was the well production rate. The range of gas production from the wells varied substantially but there was no observable correlation between production and leak rate. The highest emissions were from wells that were not producing gas at the time of the measurements. In the case of one of the non flowing wells (C3) at least, it may have been that the high well pressure due to the shut-in was contributing to the high leakage. Conversely, Well C6, which was producing about 186,000 m^3 day^{-1} (cf. the median production rate of 13,700 m^3 day^{-1}) had relatively low emissions, most of which were derived from the exhaust from the engine on the well pad.

Despite the rather low well pad emissions measured during this study, a much higher emission source was identified on a water gathering line installation. Unfortunately accurate measurements could not be made at this site but indicative estimates suggested that the emission rate from this source was at least three times higher than the largest emission rate measured on any of the wells. Similar installations are widespread through the Queensland gas regions and occasionally, gas can be heard escaping from vents on these systems. It is possible that these may be a significant source of CH_4 and is an area that needs further investigation.

5.1 Emission Factors

As discussed in Section2 emissions from equipment leaks are often estimated for NGER reporting according to Method 1 using a generic emission factor of 1.2 kg CO_2-e t^{-1}, which is equivalent to 57 g CH_4 t^{-1}. It is therefore instructive to compare this emission factor to the leak emission data measured in the field. The field measurements yielded a median leak rate 0.02 g min^{-1} and mean rate of 1.6 g min^{-1} from the 35 wells

where leaks were found. The median production rate of the wells was 13,700 m^3 day^{-1} or 9.3 t CH_4 day^{-1} (referenced to 15 °C). Dividing the median daily leak rate by the median production rate gives an emission factor of approximately 4 g CH_4 t^{-1} or 0.1 kg CO_2-e t^{-1} (based on a global warming potential of 21). Using the mean leak rate of 1.6 g min^{-1} and mean production rate of 29,600 m^3 day^{-1} yields an emission factor of 115 g CH_4 t^{-1} or 2.4 kg CO_2-e t^{-1}. This range is consistent with the current NGER emission factor for general equipment leaks and tends to confirm that equipment leaks comprise only a very small proportion of greenhouse gas emissions from CSG production.

Similar calculations may be made to develop emission factors for vents and pneumatic equipment. A summary of the emission data for leaks, vents and pneumatic equipment and the corresponding emission factors calculated from these data are shown in Table 5.2.

Table 5.2. Summary of emission data from leaks, vents and pneumatic equipment. Emissions factors calculated from the mean emission rate for each category are also shown in units of kg CO_2-e t^{-1} (GWP of 21 used in this calculation).

	Equipment Leaks	Vents	Pneumatic Equipment
Mean (g min^{-1})	1.59	6.05	0.12
Median (g min^{-1})	0.02	1.14	0.06
Std Dev	5.36	13.40	0.18
N	35	10	7
Calculated Emission Factor from Mean Emission Rate (kg CO_2-e t^{-1})	2.4	9.1	0.2

Although these averaged emission factors are low it should be remembered that firstly, the number of wells examined was less than 1 % of wells in operation so may not be representative of the total well population and secondly, there were several equipment leaks that were much higher than the average values (Figure 5.1). The maximum leak rate measured in this study was about 28 g min^{-1} on Well C3 and although this well was not flowing at the time, based on the median production rate for all wells, is equivalent to 91 kg CO_2-e t^{-1}. A high leak rate of 15 g min^{-1} was also found at Well E4 and based on its production rate, equates to 102 kg CO_2-e t^{-1}. These leak rates are about two orders of magnitude higher than the current NGER emission factor for equipment leaks.

Another important point with regard to the reliability of emission factors is that they may change due to operating conditions or maintenance. For instance, the leak from Well E4 discussed above was repaired during the site visit and completely sealed. Several other leaks were effectively repaired during the course of the visits once they were identified. However, since wells operate largely unattended, there may be some time between when the leak forms and when it is repaired.

With regard to well casing leaks there is currently no emission factor representative of Australian operations for estimating emissions. The current Method 2 emission factor is based on measurements made at some Canadian wells during the mid 1990s (CAPP, 2002). While there have been suggestions that well leakage may be a significant source of emissions (Somerville, 2012), the wells examined in this study showed no evidence of emissions via this route. But again, this needs to be considered in the context of the small number of wells examined.

6 Conclusions

Fugitive CH_4 emission rates were measured at 43 CSG well sites in Queensland and NSW. A range of methods was applied including downwind traverses of CH_4 plumes originating from well pads, and on-pad measurements to determine leak rates from individual items of equipments and well casings.

Emission rates from production sites ranged from zero to a maximum of about 44 g min^{-1}. The highest emission rate was due to CH_4 released from a vent on the well pad while the lowest emitters were two plugged and abandoned wells and a suspended well. All of the producing wells were found to have some level of emissions, although in all cases these were very low compared to overall production. Emissions were found to comprise equipment leaks, venting, pneumatic device operation and engine exhaust. The wells examined in this study did not show any evidence of CH_4 migration outside the well casing.

Overall, the median CH_4 emission rate from all sources for the wells examined was approximately 0.6 g min^{-1} while the mean emission rate was about 3.2 g min^{-1} or about 7 m^3 day^{-1}. This compares to a mean production rate of the 43 wells of 29,600 m^3 day^{-1} and represents about 0.02 % of total production. This is very much lower than recent estimates of CH_4 emissions from unconventional gas production in the United States.

Apart from vents, highest emissions were due to CH_4 leaking from seals on water pump shafts. On several occasions, these leaks were repaired on site once they were identified. The median emission rate of all the equipment leaks identified was 0.02 g min^{-1} and the mean was 1.6 g min^{-1}, which yield emission factors of about 0.1 kg CO_2-e t^{-1} and 2.4 kg CO_2-e t^{-1}, respectively. This range is consistent with the emission factor currently used in the National Energy and Greenhouse Reporting Method 1 methodology for estimating equipment leaks.

Although well pad emissions were generally found to be low, one significantly higher emission source was found on a vent associated with a water gathering line. This source appeared to be at least three times higher than the highest emission rate from any well examined.

The results obtained in this study represent the first quantitative measurements of fugitive emissions from the Australian CSG industry; however, there are a number of areas that require further investigation. Firstly, the number of wells examined was only a very small proportion of the total number of wells in operation. Moreover, many more wells are likely to be drilled over the next few years. Consequently the small sample examined during this study may not be truly representative of the total well population. It is also apparent that emissions may vary over time, for instance due to repair and maintenance activities. To fully characterise emissions, a larger sample size would be required and measurements would need to be made over an extended period to determine temporal variation.

In addition to wells, there are many other potential emission points throughout the gas production and distribution chain that were not examined in this study. These include well completion activities, gas compression plants, water treatment facilities, pipelines and downstream operations including LNG facilities. Emissions from some of these sources are often estimated for reporting purposes using methodology based on emission factors largely derived from the U.S. gas industry. However, reliable measurements on Australian facilities are yet to be made and the uncertainty surrounding these some of these estimates remains high.

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Appendix

Table A1. Results of the downwind traverse measurements for each well. The average results shown for Wells B2, B7 and C3 were measured on each well pad. All units are g min^{-1}.

Well Number	Average	Minimum	Maximum	Std Deviation
A1	0.04	0.03	0.11	0.03
A2 - Suspended	0.00	0.00	0.00	0.00
A3	0.04	0.02	0.08	0.02
A4	7.28	2.75	13.42	3.38
A5	0.10	0.08	0.20	0.06
A6	0.05	0.04	0.05	0.01
B1	1.50	0.01	3.60	1.22
B2	43.8 (on pad)	1.09	66.5	22.5
B3	0.07	0.01	0.28	0.08
B4	0.04	0.01	0.22	0.06
B5	0.01	0.01	0.02	0.00
B6	1.66	0.77	3.10	0.74
B7	1.27 (on pad)			
B8	1.31	0.10	2.85	0.98
B9	0.83	0.14	2.95	0.81
B10	0.15	0.07	0.28	0.07
B11	1.79	0.09	3.65	1.07
B12	0.05	0.01	0.12	0.03
B13	0.02	0.01	0.06	0.02
B14	0.61	0.01	3.23	0.98
B15	1.61	0.11	7.78	2.35
C1	8.69	2.73	15.9	4.77
C2	1.10	0.33	2.45	0.66

C3	28.0 (on pad)			
C4	11.8	0.46	34.8	12.4
C5	0.93	0.21	1.82	0.56
C6	1.17	0.07	2.38	0.71
C7	0.54	0.04	0.99	0.35
C8	0.10	0.02	0.27	0.08
C9	0.05	0.01	0.10	0.03
C10	1.75	0.76	3.52	0.82
C11	0.07	0.05	0.10	0.02
D1 Abandoned	0.00	0.00	0.00	0.00
D2	0.12	0.03	0.16	0.04
D3 Abandoned	0.00	0.00	0.00	0.00
D4	0.32	0.17	0.57	0.13
D5	1.07	0.11	2.18	0.71
D6	2.52	0.44	5.00	1.42
E1	2.17	0.63	4.08	1.19
E2	0.99	0.50	2.17	0.55
E3	0.60	0.22	1.13	0.33
E4	14.8	1.89	56.8	18.8
E5	0.06	0.01	0.19	0.06

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FOR FURTHER INFORMATION

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