REPORT

NSW CHIEF SCIENTIST AND ENGINEER

INDEPENDENT REVIEW OF THE COAL SEAM GAS ACTIVITIES IN NSW

BACKGROUND PAPER ON HORIZONTAL DRILLING

Prepared for

NSW Chief Scientist and Engineer

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1 OVERVIEW

This background paper focuses on the technology known as 'horizontal drilling' and includes a discussion of its origins, the various types and uses of horizontal drilling, and in particular its use in the extraction of coal seam gas (CSG) in Australia. A major purpose of this background paper is to provide a review of horizontal drilling in the context of coal seam gas, and in doing so, to communicate and place in context the potential risks that are associated with horizontal drilling and some of the mitigation strategies to manage these risks. It also identifies some areas for further research aimed at closing the gaps in our knowledge of this technology as it is applied to CSG operations.

This background paper was prepared by Emeritus Professor John Carter in response to a request from the Office of the New South Wales Chief Scientist and Engineer. The paper was formally commissioned under a contract between The Department of Trade and Investment and Advanced Geomechanics, dated 6 June 2013. The terms of reference for this study are provided as Appendix A.

2 DISCLOSURE

John Carter is Emeritus Professor and former head of the Faculty of Engineering and Built Environment, The University of Newcastle. He is also Consultant Director of the specialist geotechnical consultancy known as Advanced Geomechanics, based in Perth, WA. He was previously retained by the Office of the NSW Chief Scientist and Engineer (through Advanced Geomechanics) to provide a review opinion on the recent NSW Coal Seam Gas Draft Codes of Practice.

Advanced Geomechanics has provided specialist advice related to aspects of geotechnical design for several coal seam gas (CSG) projects in Queensland, specifically in relation to the physical infrastructure required to export the gas from the CSG field onshore to the terminals at Curtis Island. Advanced Geomechanics has not provided any advice or technical services in relation to gas reservoirs, borehole mechanics or gas extraction for these projects.

3 INTRODUCTION

'Natural gas' is the term applied to a combustible mixture of hydrocarbon gases that naturally occur in rock formations. The main constituent is usually methane (CH_4), but it may also contain varying amounts of heavier hydrocarbons and other gases such as carbon dioxide. Natural gas is formed by the alteration of organic matter and often it is trapped underground in subsurface reservoirs formed by the folding and/or faulting of sedimentary rock layers. When a deposit of this gas can be readily extracted from these reservoirs it is known as 'conventional gas'. Conventional gas can also be found together with oil in oil fields.

'Unconventional gas' is found in deposits trapped underground within relatively deep geological formations, often within shale formations or coal measures or tight sandstone deposits. The major constituent of 'unconventional gas' is also methane. Until recently, mining for unconventional gas in such deposits was technically difficult and therefore simply not economically viable. However, recent innovations have brought about a change in this situation, rendering viable the economic extraction of unconventional gas from such gas fields. In particular, with advancements in technology, especially in horizontal drilling and hydraulic fracturing, these resources are becoming increasingly more viable and economically attractive for development.

According to the CSIRO, Australia has significant known and potential resources of unconventional gas trapped in the rocks of the earth's crust as coal seam gas (CSG), tight gas and shale gas, all of which could become a considerable source of energy supply for the nation over the longer term. "CSG and tight gas resources are currently being developed or are close to development in Australia whereas shale gas exploration is in its infancy – the first vertical wells specifically targeting shale gas were drilled in the Cooper Basin in early 2011, and Santos has just announced what they believe to be the first commercial production of shale gas in Australia" (CSIRO, 2012).

Coal seams are often abundant sources of methane and therefore have been the subject of much recent interest by those involved in extracting unconventional gas. Indeed, the presence of methane gas in coal has been well known to coal miners as a safety hazard for a long time, but it is also now being viewed as a potential source of usable energy. There are now many cases of the gas being extracted from coal seams for commercial and domestic use, both in Australia and overseas.

The composition of 'coal bed methane' or 'coal seam gas' is, as one of these names suggests, predominately methane, but it can also include other constituents, such as ethane, carbon dioxide, nitrogen and hydrogen. The gas is normally bound or 'adsorbed' in the micropore structure of the coal, rather than being available as free gas in the voids of the coal. The adsorbed gas remains bound to the coal under the pressure exerted by groundwater. However, this adsorbed gas is able to diffuse into the natural fracture network present in the coal when a pressure gradient exists between the coal matrix and its fracture network. Such a pressure difference could arise, for example, due to pumping groundwater from the coal seam. The fracture network in coal seams usually consists of a regular system of microfractures called 'cleats'. When gas is extracted from the coal seam, it normally flows through these microfractures to a production well.

In order to facilitate extraction of the gas, horizontally drilled production wells may be employed, sometimes together with hydraulic fracturing of the coal seam to enhance its effective permeability and therefore increase the rate of gas extraction. The main purpose of drilling these wells horizontally, or near to horizontal, along the coal seam, is to increase the access to the coal and the trapped gas by increasing the conductive pathways from the coal seam to the well and ultimately to the ground surface. However, horizontal drilling can also increase the difficulty of properly sealing a well, in part due to the increased difficulty in obtaining a uniform thickness of cement annulus around the casing tube(s), which in turn may increase the likelihood of leaks and consequential pollution issues, unless there is very close control over the drilling operation and the casing and cementing process adopted to seal the borehole from the surrounding rock mass.

This background paper focuses on the technology known as 'horizontal drilling' and includes a discussion of its origins, the various types and uses of horizontal drilling, and in particular its use in the extraction of coal seam gas (CSG) in Australia. A major purpose of this background paper is to provide an overview of horizontal drilling in the context of coal seam gas, and in doing so, to communicate and place in context the potential risks that are associated with horizontal drilling.

4 WHAT IS HORIZONTAL DRILLING?

'Horizontal drilling' can be defined as a special case of 'directional drilling' where the well or borehole being drilled, usually by rotary drilling techniques, is deviated onto a horizontal plane. 'Directional drilling' is defined as the intentional deviation of a wellbore from the path it would naturally take (Royal Society, 2012).

Vertical, or near vertical boreholes drilled from the ground surface have been used for many years in the petroleum industry for both exploration and production purposes. They are also commonly used in mineral exploration and the development of mineral resources, for exploration in civil and mining engineering, geotechnical engineering and hydrogeology, and also to recover groundwater. Such boreholes or wellbores are usually drilled using sections of steel pipe joined together, called a drill string, and with a special drilling bit located at the bottom of the drill string.

It is important to note that not all wellbores are vertical. Drilling inclined wellbores has been common practice in the petroleum industry since at least the 1920s.

In the early stages of the history of rotary drilling, the pipe connecting the drilling apparatus at the ground surface and the cutting bit at the bottom of the pipe, or drill string, were all rotated together by a motor located at the ground surface. Eventually, it proved more efficient in some situations to locate the rotational motor at the bottom of the borehole, thus removing the necessity of rotating the entire drill string. These downhole drilling motors (also known as mud motors) are activated by the hydraulic power of the drilling mud circulated down through the hollow drill string. This mud is also used to cool the drill bit and to remove the drill cuttings from the borehole. The drilling mud then returns to the surface in the annular void between the drill string and the wall of the borehole. This fluid is generally recirculated after the drill cuttings borne by the drilling mud are removed at the surface.

Major advances in directional drilling occurred in the 1970s when downhole drilling motors became more common and developments were also made in instruments, particularly those related to remote sensing and data communication, that allowed the effective monitoring of the drill performance and the control of its actions. The latter tools allowed directional data and drill performance data to be sent back to the surface without disturbing the drilling operations. Importantly, they also allowed adjustments to be made to the direction being drilled. In other words, the drill could be effectively 'steered' from the bottom of the drill hole, with control being possible from the ground surface.

These important technological advances soon found great application in the field of petroleum engineering. With the development of directional drilling technology, wellbores could be drilled horizontally as well as vertically, or at any desired inclination and in any plan direction, thus allowing significantly increased access to the petroleum resource from a single location on the ground (or sea) surface.

5 TYPES AND APPLICATIONS OF HORIZONTAL DRILLING

Since the initial developments of directional drilling in the petroleum industry, the technology has found a variety of important uses, especially in civil and mining engineering, together with its original use in petroleum engineering.

Today, the practice of directional drilling can be broken down into three main groups: Oilfield Directional Drilling (ODD) which was the original application of this technology, Horizontal Directional Drilling (HDD) for the installation of utilities, usually at relatively shallow depths, and

Horizontal In-Seam Drilling (HID) usually conducted at much greater depth for the extraction of unconventional gas from coal seams or shale formations.

5.1 Oilfield Directional Drilling

The first recorded use of a horizontal well tapped into oil reserves was near Texon, Texas in 1929. Another was drilled in 1944 in the Franklin Heavy Oil Field, Venango County, Pennsylvania, at a depth of 500 feet. China tried horizontal drilling for petroleum as early as 1957, and later the Soviet Union also tried the technique (Helms, 2008).

However, as already indicated, little practical application occurred until the 1970s and early 1980s when the advent of improved downhole drilling motors became common, and the invention of downhole telemetry equipment provided a means of guiding the horizontal drilling.

Tests carried out by the French company, Elf Aquitaine, between 1980 and 1983 in four horizontal wells drilled in southwestern France and offshore Italy indicated that commercial success of horizontal drilling could be achieved. Early production well drilling was subsequently undertaken by British Petroleum in Alaska’s Prudhoe Bay Field using horizontal drilling techniques, in a successful attempt to minimize unwanted water and gas production (Helms, 2008).

Today, the use of horizontal drilling technology to recover conventional oil and gas reserves is widespread in the petroleum industry and it is now considered to be a mainstream technology. A schematic illustration of the process of oilfield directional drilling is provided in Figure 1.

5.2 Horizontal Directional Drilling

Horizontal Directional Drilling (HDD) was developed in the 1970s by combining techniques used in conventional geotechnical boring and those used in oil and gas directional drilling. HDD has been used since that time to install utility crossings under a vast range of surface obstacles, including rivers, roads and railways. There are now many instances of its use in NSW and elsewhere in Australia and numerous contractors are available to provide this service. (For example, a search of the internet using the phrase ‘Australian directional drilling services’ will provide a large list of contractors and their completed projects.)

In particular, this technology allows for the installation of utilities including gas, water and sewer pipes, as well as electricity and communications cables, without the usual social costs associated with open trench installations, thus largely avoiding the disruption of traffic flows, damage to highways, walkways, driveways, lawns and gardens.

This technology is also used to install pressure sewer systems for water authorities because it is has proven to be far more cost effective than open trench construction. Indeed, main trunk lines can now be bored down streets and branches can be installed into houses under garden areas, driveways and paths efficiently and effectively, without the major disruption of conventional trench technology.

Horizontal directional drilling is characterised by its use at relatively shallow depths, from the surface down perhaps as far as ten or twenty metres. It can be used to install cables and conduits from a few centimetres in diameter to pipelines as much as about a metre or more in diameter. At these relatively shallow depths it is used most commonly to create a horizontal or near horizontal borehole through soil and unconsolidated surficial sediments, but the technology can also be adapted to drill horizontally through competent rock.

This type of horizontal drilling technology usually involves the use of a steerable drill bit, approximately 90 mm in diameter, which is launched from the ground surface at an initial inclination (or dip) of approximately 10 to 15 degrees to the horizontal. Drilling continues and the drill bit is steered from the surface until it emerges at the desired location, thus producing an initial pilot hole. In soil it is common practice for the drill bit to be followed by a 125 mm diameter washover pipe, which enlarges the diameter of the pilot hole as it is being advanced.

Upon completion of the pilot hole, the drill string is either removed by pulling a reaming tool back through the hole, or a revolving barrel reamer is pulled back along the washover pipe. Subsequent reaming continues until the required diameter of the borehole is obtained. Drives of more than 1000 metres and up to 1 metre in diameter have been successfully carried out using this technology.

Horizontal directional drilling is usually achieved with the assistance of a viscous fluid known as drilling mud. It is a combination of water and, commonly, the clay mineral bentonite or an appropriate polymer. This fluid is continually pumped to the cutting head or drill bit, facilitating the removal of cuttings, stabilizing the bore hole, cooling the cutting head, as well as acting as a lubricant to assist the insertion and passage of the final product pipe or cable.

A schematic representation of horizontal directional drilling is provided in Figure 2 and an example of the type of equipment used to conduct this type of drilling is shown in Figure 3.

5.3 In-seam Drilling

Horizontal drilling, using in-seam rotary drilling techniques, has been used since at least the 1990s for the extraction of natural gas from unconventional sources, such as shale beds and coal seams that can lie deep underground. In such cases the well, which usually begins as a vertical bore, may extend hundreds and perhaps even thousands of metres beneath the ground surface. As the vertical wellbore approaches the rock formation containing the unconventional gas it begins to deviate from the vertical, tracing out a wide bend or curve until it runs parallel to the shale formation or the coal seam.

Multiple horizontal wells or legs can go in different directions at the kickoff point, defined as that point where the well bore begins to curve away from the vertical. Eventually, the horizontal portion of the leg can stretch for a kilometre or more and make the combined vertical and horizontal wellbore several kilometres in length. Horizontal drilling of this type allows one surface well to branch out underground and tap natural gas resources contained in deep, broad and thin shale beds and coal seams. Horizontal branches may also be drilled within the seam, emanating from one of the original horizontal wells. In this way coverage of the seam and extraction of the gas can be maximised.

Probably the first horizontal well of this type was completed in the Barnett Shale in Texas in 1993. A succession of wells, which included horizontal drilling, soon made Barnett the most productive and highly developed shale gas reservoir in the world. Since then, advances in horizontal drilling, together with parallel advances in hydraulic fracturing, have transformed numerous shale gas reservoirs into major sources of natural gas. The first generation of modern horizontal drilling expanded rapidly into naturally fractured formations such as Texas' Austin Chalk and North Dakota's upper Bakken Shale (Shalegaswiki, 2010). Today, many companies are trying to replicate the Barnett success story in shale reservoirs and coal seams all over the world.

A schematic representation of an in-seam horizontal drilling operation, as described above, is provided in Figure 4.

It should be noted that in-seam drilling is not always conducted from the surface where deviation of the borehole from the vertical is a requirement. It can also be carried out from within underground coal mines. In such cases, horizontal or inclined but essentially straight boreholes are drilled along the coal seam. This technique has been used extensively in Australia and is regarded as "the frontline mitigation technique for dealing with hazardous gas" (Thompson and Qzn, 2009) in the underground mining of coal seams. The purpose of drilling these boreholes is to extract some of the gas trapped in the coal seam, thus also reducing the pressure in the coal seam, which then assists in making coal extraction safer. A review of this type of in-seam drilling practice was the focus of a relatively recent ACARP project conducted by Thompson and Qzn (2009).

6 HISTORY OF UNCONVENTIONAL GAS EXPLORATION IN AUSTRALIA

Australia has a long history of petroleum exploration. For example, in South Australia the first well was sunk adjacent to the Otway Basin in the search for oil in 1866 (SA, 2013). In the 1950s the early Palaeozoic sediments in the northeast of South Australia were the focus of effort until gas was discovered in the overlying Permo Carboniferous section of the Cooper Basin in the early 1960s. The Cooper and Eromanga basins, which span north eastern South Australia and south western Queensland, are now Australia's largest onshore petroleum production areas.

AGL commenced the first coal seam methane exploration drilling in the Cooper Basin region in South Australia in 2009. The first well to test shale gas potential in the Cooper Basin, Encounter 1, was drilled in 2010 by Beach Energy. To date, only one unconventional gas well has been drilled in the Queensland portion of the basin (QLD, 2012). Significant exploration activity has continued since the first successful strikes in the Cooper basin. For example, during 2010-11, Santos announced gas flows from various coal seams, Stuart Petroleum published its own significant resource estimates for shale gas, AGL continued to test for CSG, Strike tested the shallowest Permian coals for CSG in the southern Cooper Basin, and Santos continued to exploit tight gas in the same basin.

Queensland has a series of sedimentary basins ranging in age from Mesoproterozoic to Quaternary and many of these basins are likely to be prospects for finding unconventional gas. Exploration for conventional petroleum began in earnest in Queensland in 1960 and targeted most basins across the state. Exploration success resulted in activity becoming focused on the Bowen, Surat, Cooper and Eromanga basins. Today these basins have become the key petroleum-producing regions of the state. Recently, significant coal seam gas (CSG) reserves have been discovered in the Bowen and Surat basins, and indeed CSG is now providing most of the state's gas requirements. Exploration for other forms of unconventional petroleum, such as shale gas and tight gas, is only just beginning in Queensland. Overall, the state's coal seam gas (CSG) industry has grown rapidly over the past 15 years — the annual number of wells drilled has increased from 10 in the early 1990s to almost 600 in 2010–11 (QLD, 2012).

In New South Wales there has been a dramatic increase in petroleum title applications over the past few years. To date the most active coal seam gas exploration activity has taken place in the Hunter Region, Gloucester Basin, Gunnedah Basin, Southern Coalfields (near Camden) and the Clarence Moreton Basin in north eastern New South Wales. As noted by a recent report of Standing Committee 5 of the NSW Parliament (NSW, 2012), activity to date has been mostly limited to exploration, with only a small number of coal seam gas projects given approval to commence production, including the Camden Gas Project and the Gloucester Gas Project – both by AGL Energy Limited, the Narrabri Gas Project – by Santos, and the Richmond Valley Power Station and

Casino Gas Project – by Metgasco. Only two of these developments, at Camden and Narrabri, are currently producing coal seam gas.

Currently Western Australia's shale and tight gas industry is in the early exploration and proof of concept phases. The process of horizontal drilling combined with hydraulic fracture stimulation is likely to be required to extract natural gas typically found in the shale and tight rock formations located between two to five kilometres underground in WA. In 2012, three petroleum exploration wells were subjected to hydraulic fracturing in the Mid-West region of WA. However, according to the Western Australian Department of Mines and Petroleum, as of May 2013, there are currently no plans for any further petroleum wells in WA to undergo hydraulic fracturing (WA, 2013).

In Victoria, exploratory drilling for coal seam gas has occurred since 2000 in Gippsland, the Otways and Bacchus Marsh. Based on evidence to date, the nature of Victoria's coal resource may not require hydraulic fracturing in order to get coal seam gas to flow, and in fact the Victorian government has imposed a temporary ban on the use of hydraulic fracturing. The Victorian Department of Primary Industries has noted that, even with black coal seams, hydraulic fracturing is only used in a small number of cases. For example, the Victorian Department has observed that hydraulic fracturing has been used in Queensland in only 8 per cent of cases (VIC, 2012).

Exploration for petroleum in the Northern Territory led to the discovery of oil and gas at Mereenie in 1964 and gas at Palm Valley in 1965. Petroleum basins have also been analysed and a number of 'unconventional' gas targets have been identified. According to the Northern Territory Department of Mines and Energy "a number of potential shale gas targets have been identified, although there may also be 'tight' gas which is gas trapped in a non-organic impermeable rock such as sandstone or limestone. … There are currently no known coal seam gas prospects in the Territory." (NT, 2012).

7 HORIZONTAL DRILLING FOR UNCONVENTIONAL GAS IN AUSTRALIA

The use of horizontal drilling technology for the recovery of unconventional gas is a relatively recent phenomenon in Australia. For example, the first horizontal well was successfully drilled, completed and tested in South Australia in 1993 in the Cooper Basin. It is known as the Meranji 14H well.

Santos has been operating the Cooper Basin Joint Venture for over 50 years, producing gas from conventional and tight formations since 1969. In 2004 Santos established a dedicated unconventional reservoir team and has since drilled a number of wells targeting shale formations at levels below the conventional reservoirs. Santos' objective is to deliver commercial production by 2015, and a key to this program is the optimisation of horizontal wells, including optimum horizontal lengths and the adoption of hydraulic fracturing programs and techniques. It has not been possible to ascertain how many horizontal wells have been drilled to date for unconventional gas in the Cooper basin.

In the Moranbah and Moura areas of Queensland the natural permeability of the coal seams is relatively low and so in-seam (or horizontal) drilling is often employed to enhance gas production. To date, development has concentrated on coal seams at around 300 metres below the surface in order to avoid the reduction of permeability that is generally associated with increasing depth. As for the Cooper basin, it has not been possible to ascertain how many horizontal wells have been drilled in Queensland for CSG extraction.

AGL's Camden Gas Project in New South Wales is a good example of the application of horizontal drilling in the extraction of CSG. AGL has made public some of its data concerning the use of horizontal drilling and also hydraulic fracturing (AGL, 2013a). In this project AGL identified a number of locations to access the coal seams by drilling horizontally directly into the coal, using knowledge of the local geology. In this project area the Bulli and Balgownie coal seams have been targeted for gas extraction. They are located between 600-800 metres below the earth's surface. The use of horizontal drilling has reduced the number of vertical wells required to extract the gas and it has also minimised surface disturbance. AGL's Camden Gas Project currently consists of 144 wells (as at October 2012) and currently supplies around 5% of the NSW gas market. Only 89 of those wells are currently producing gas. AGL claims that in New South Wales it has used hydraulic fracturing on approximately 85% of the total wells it has drilled to date for the extraction of CSG (AGL, 2013b). The other 15% of the wells drilled have been horizontal wells, none of which required fracture stimulation. In other words, over the past 12 years AGL has used hydraulic fracturing in 117 of 144 wells drilled as part of the Camden Gas Project. The remaining 27 wells have used horizontal drilling without the additional measure of hydraulic fracturing in order to stimulate gas recovery.

8 HORIZONTAL DRILLING METHODS

The process of creating a horizontal well in a coal seam can generally be summarised as follows:

- A wellbore is first drilled vertically from the surface using conventional vertical drilling techniques. This vertical wellbore should be taken well below any surface or intermediate aquifers containing potable water.
- The drill string is then removed from the hole and casing (usually metal) is installed over the full current depth of the wellbore.
- Cement is then pumped down the middle of the casing tube to the bottom of the borehole and allowed to flow back to the surface in the annular void between the casing and the surrounding rock. The important purpose of the cement and the casing is to seal the wellbore from the surrounding rock formation, thus preventing any leakage of gas or other contaminants used in the drilling process and preventing these substance from coming in contact with the groundwater. This section of cemented casing is generally known as the 'surface casing'.
- In best practice, this casing would then be pressure tested to ensure a complete seal so that no gas will escape into the rock formation once gas production commences.
- If necessary, vertical drilling is continued until a suitable distance is reached above the target coal seam.
- Usually the newly drilled section of the wellbore is then cased in a manner similar to that adopted to case the upper section of the wellbore. Obviously this will entail the use of a smaller diameter casing pipe placed concentrically within the surface casing. If installed, this is generally known as 'intermediate casing' or 'production casing' if it is the final layer of casing to be installed.
- A downhole drill is then lowered on the drill string to the bottom of the existing well bore.
- By appropriately steering the downhole drill, the wellbore is then gradually deviated from the vertical, in a controlled manner, until it intersects and eventually runs along the coal seam.
- The wellbore is subsequently drilled horizontally into the coal seam using the downhole drill for a total horizontal distance up to 3,000 metres.

As previously noted, horizontal drilling into the coal seam is a form of stimulating the coal to increase conductive pathways from the coal seam into the well and to the surface. In some cases, this technique also eliminates the need to further stimulate the coal seam by hydraulic fracturing in order to enhance production. If hydraulic fracturing of the coal is not required, the in-seam section of the well bore usually remains unlined by further casing, thus provide the maximum possible surface area across which the gas may flow into the horizontal section of the wellbore. It is noted that the permeability of coal is usually much higher (often by orders of magnitude) than the permeability of gas-bearing shale deposits, and it is largely for this reason that hydraulic fracturing may not be required in coal, whereas it is normally required in shale.

When horizontal drilling is used to extract gas from shale deposits in conjunction with hydraulic fracturing, the following additional steps will be required:

- After the horizontal section of the wellbore has been drilled, production casing is then run until the end of the well bore and cemented into the formation.
- The section of the production casing in the targeted region of the deposit is then perforated with a device to allow the gas to flow into the production casing.
- If required, gas flow may then be stimulated further by fracturing the rock formation with a pressurized mixture of sand, water and chemicals.

Informative animations illustrating the process of horizontal drilling combined with hydraulic fracturing in the recovery of shale gas can be found at:

- http://www.oerb.com/Default.aspx?tabid=242,
- http://www.youtube.com/watch?v=O0kmskvJFt0, and
- http://www.api.org/oil-and-natural-gas-overview/exploration-and-production/hydraulic-fracturing/hydraulic-fracturing-safe-oil-natural-gas-extraction.

A separate animation illustrating just horizontal drilling can also be found at:

- http://www.youtube.com/watch?feature=player_embedded&v=Y37XbMEDnXc.

In particular, some of these animations show the horizontal section of the well bore being lined by production casing preparatory to hydraulic fracturing of the surrounding shale. As previously mentioned, and in contrast to the usual situation with shale gas extraction, the practice of placing casing in the horizontal section of the wellbore is often not adopted in the extraction of coal seam gas in Australia. Indeed, AGL has reported (AGL, 2013a) that by not using casing in the horizontal boreholes in its NSW coal seam gas operations, the need for hydraulic fracturing of the coal was avoided.

An illustration of the type of casing system used by AGL in the surface region for the extraction of CSG is illustrated in the Figure 5. Note the multiple barriers preventing leakage of gas into the groundwater in the upper zone of the wellbore.

An illustration of the casing system typically adopted in the extraction of shale gas from horizontal wells is illustrated in the Figure 6. Again, note the multiple barriers designed to prevent leakage of gas and other potential contaminants from the wellbore.

The design of horizontal wells has evolved steadily since the first wells of this type were drilled and today it is possible to drill multiple horizontal well paths from each surface location. This clustering of wells onto a single surface location is often referred to as 'pad-based drilling' and it has resulted in a dramatic reduction in the overall amount of land required for well locations. A video displaying an example of pad-based drilling in Australia can be seen at the following web site:

- http://www.youtube.com/watch?v=NCdkybhPb6w.

The evolution of drilling methods and the concept of pad-based drilling are illustrated schematically in Figures 7 and 8.

9 WELL INTEGRITY RISKS

A joint study was conducted in 2012 by the Royal Society and the Royal Academy of Engineering into the extraction of shale gas in the United Kingdom using hydraulic fracturing (Royal Society, 2012). This study identified well integrity as an important factor in these operations, and indeed the lack of integrity as a possible risk to be avoided or mitigated. Many of the findings and recommendations of this joint study are also relevant to the extraction of coal seam gas using horizontal drilling. The following is a pertinent extract from this joint report on the very significant issue of well integrity.

> "'Well integrity' refers to preventing [unconventional] gas from leaking out of the well by isolating it from other subsurface formations (API, 2009). The isolation is provided according to how the well is constructed. A series of holes ('wellbores') of decreasing diameter and increasing depth are drilled and lined with steel casing joined together to form continuous 'strings' of casing (see [Figure 6]):

- **Conductor casing**. Set into the ground to a depth of approximately 30 metres, the conductor casing serves as a foundation for the well and prevents caving in of surface soils.
- **Surface casing**. The next wellbore is drilled and sealed with a casing that runs past the bottom of any freshwater bearing zones (including but not limited to drinking water aquifers) and extends all the way back to the surface. Cement is pumped down the wellbore and up between the casing and the rock until it reaches the surface.
- **Intermediate casing**. Another wellbore is drilled and lined by an intermediate casing to isolate the well from non-freshwater zones that may cause instability or be abnormally pressurised. The casing may be sealed with cement typically either up to the base of the surface casing or [preferably] all the way to the surface.
- **Production casing**. A final wellbore is drilled into the target rock formation or zone containing shale gas. Once fractured, the shale gas [flows] into the well. This wellbore is lined with a production casing that may be sealed with cement either to a safe height above the target formation up to the base of the intermediate casing; or all the way to the surface, depending on well depths and local geological conditions."

> "Well failure may arise from poor well integrity resulting from:

- **Blowout**. A blowout is any sudden and uncontrolled escape of fluids from a well to the surface.
- **Annular leak**. Poor cementation allows contaminants to move vertically through the well either between casings or between casings and rock formations.
- **Radial leak**. Casing failures allow fluid to move horizontally out of the well and migrate into the surrounding rock formations."

Clearly, these types of failures must also be avoided in any coal seam gas operation. The use of multiple barriers in the form of well-constructed wellbore casing is critical in this regard. These casing systems should be inspected and pressure tested prior to the well's production phase in order to ensure their integrity.

10 BEST PRACTICE FOR HORIZONTAL WELL CONSTRUCTION

Since 1924, The American Petroleum Institute (API) has been a leader in the development of equipment and operating standards for the oil and natural gas industry. Most of the important standards produced by the API have been based on best practice activities developed in the petroleum sector. One document of particular relevance to horizontal drilling is the API Guidance Document HF1 – "Hydraulic Fracturing Operations – Well Construction and Integrity Guidelines" (API, 2009). The fundamental principle upon which this document is based is the protection of groundwater and the environment. In this regard, API offers the following comments.

> "Groundwater is protected from the contents of the well during drilling, hydraulic fracturing, and production operations by a combination of steel casing and cement sheaths, and other mechanical isolation devices installed as a part of the well construction process. It is important to understand that the impermeable rock formations that lie between the hydrocarbon producing formations and the groundwater have [in many instances] isolated the groundwater over millions of years. The construction of the well is done to prevent communication (the migration and/or transport of fluids between these subsurface layers).
>
> "The primary method used for protecting groundwater during drilling operations consists of drilling the wellbore through the groundwater aquifers, immediately installing a steel pipe (called casing), and cementing this steel pipe into place. … The steel casing protects the zones from material inside the wellbore during subsequent drilling operations and, in combination with other steel casing and cement sheaths that are subsequently installed, protects the groundwater with multiple layers of protection for the life of the well."

Obviously, a very good way to make an assessment of what constitutes best practice is to learn the lessons of the past and to avoid the mistakes of the past. In this respect, the joint UK academies report on hydraulic fracturing in the extraction of shale gas noted the following.

> "Studies in North America have used well data to identify key factors affecting leakage, especially the number of casings and the extent to which these casings were cemented. Some of the leaky wells in a Canadian study had only a single casing or were left uncased except in the section from the surface casing down to just below the aquifer (Watson and Bachu, 2009). Others had not been cemented at all or the cementation had not reached the required height (Watson and Bachu, 2009). Several percent of older oil and gas wells leaked, while fewer than 0.5% of those constructed since 2000 according to stricter standards were found to be leaky (Watson and Bacchu, 2009).
>
> "In the USA, it is common to have two strings of casings. When intermediate casing is not installed, cementing the production casing to the surface should be considered (API, 2009). Intermediate casing is not always cemented all the way back to the surface. At a minimum, the cement should extend above any exposed water or hydrocarbon bearing zones (API, 2009). In some states, such as Pennsylvania and Texas, there is a requirement to cement casing to approximately 22 metres (75 feet) below any aquifers. Failure to do this can lead to groundwater contamination as occurred in Pavillion, Wyoming (Di Giulio et al., 2011). In the UK, standard practice is to have three strings of casing with at least two (intermediate and production casing) passing through and thereby isolating any freshwater zones.
>
> "Best practice is to cement casings all the way back to the surface, depending on local geology and hydrogeology conditions." (Royal Society, 2012)

In all coal seam gas operations best practice methodologies for horizontal well construction should always be developed and implemented. These should include the following.

- Measurements of the groundwater should be made prior to any CSG operations in order to provide a baseline to assess any subsequent claims of water contamination.
- If hydraulic fracturing is adopted, microseismic monitoring should be carried out to ensure that fracture growth is constrained to producing formations.
- Pressure testing of the casing and the logging of the cement bond should be conducted, to verify that the rock formations have been properly isolated.
- Inspections should be carried out to confirm that operators have effectively remediated any defective well cementation.
- Inspections should also be carried out at safety-critical stages of well construction and hydraulic fracturing.
- The composition of water should be monitored and publicly reported at each stage of gas extraction, including the transport of water and waste fluids to, and from, well sites.
- Staff employed to carry out CSG operations should be well trained in all procedures and should have good knowledge of the major risks and the mitigation strategies to be adopted, as well as the legislation and other regulations that apply to their activities.

10.1 NSW Codes of Practice

Primary responsibility for the regulation of the coal seam gas (CSG) industry in NSW rests with the Division of Resources and Energy in NSW Trade & Investment. Other government agencies also have significant roles, including the NSW Office of Water.

The Division of Resources and Energy has recently developed two Codes of Practice for CSG activity. These cover hydraulic fracturing activities and well integrity and they have been prepared to strengthen the controls applying to CSG exploration and production and, importantly, to ensure current best practices are followed. Specifically, these codes contain many requirements designed to protect groundwater and surface water resources. Petroleum title holders are required to comply with the codes as a condition of their licence and these conditions are enforceable under the Petroleum (Onshore) Act 1991. Details of both codes of practice can be found at:

- http://www.nsw.gov.au/sites/default/files/uploads/common/CSG-wellintegrity_SD_v01.pdf
- http://www.nsw.gov.au/sites/default/files/uploads/common/CSG-fracturestimulation_SD_v01.pdf

11 POTENTIAL IMPACTS OF HORIZONTAL DRILLING

Horizontal drilling activities for unconventional gas have the potential to affect the environment in a number of different ways. Some of these potential impacts have been mentioned previously. The most obvious and significant impacts and some of the methods to control, mitigate or minimise them are discussed in the following sub-sections under the headings: Surface impacts, Noise, Aquifers, Coal seam water, Subsidence, and Induced seismicity. Potential impacts and risks of other forms of horizontal drilling are also discussed. An example comparison of the scale of horizontal well drilling compared to that of more conventional vertical wells is also provided.

11.1 Surface impacts

Any project that involves horizontal drilling for unconventional gas will necessarily require the establishment of significant surface facilities. In the short term, these will include the well pad, drilling equipment, water management and ancillary equipment, possibly temporary accommodation for personnel and the construction of access roads. In the longer term, a wellhead is required and surface or buried pipelines will need to be established to convey the produced gas to consumers.

Normally, it will be desirable to minimise the permanent changes to the landscape and the overall impact on the environment caused by these activities. The following measures are examples of how these changes may be minimised.

- When horizontal drilling is conducted the wells may be spread out more than if vertical wells alone are employed. Typically, vertical wells at about 800 metre spacing can be replaced by the use of horizontal wells at about 4,000 metre spacing. Thus from a production area perspective, it is reasonable to consider one horizontal well as the approximate equivalent of at least $4{,}000^2/800^2 = 25$ vertical wells. This means that fewer well heads are required, thus also requiring fewer access roads. As previously mentioned, the overall footprint should be reduced when horizontal wells are adopted to produce the gas.
- The visual impact on the environment and any potential permanent disruption to surface access can be removed if all pipelines are buried.
- Similarly, the visual impact of well activities can be significantly reduced if the wellhead facilities are also buried or disguised.

11.2 Noise

There will be unavoidable noise impacts for those living in close proximity to a drill site. Drilling operations are the noisiest phase of well development and often continue 24 hours a day during the drilling period. Noise sources during this time include various drilling rig operations, pipe handling, the use of compressors, and the operation of trucks, backhoes, tractors and cement mixing. In most instances, the closest receptor is the residence of the property owner where the well is located. Most if not all of this noise impact is likely to be only short term and can be mitigated with siting restrictions and setback requirements. Since noise control is most effectively addressed at the siting and design phase it is important that the well pad be properly located and planned. Clearly, horizontal drilling has the distinct advantage over vertical well drilling of providing the necessary flexibility to accommodate these siting requirements.

11.3 Aquifers

Because gas bearing coal seams and shale deposits are normally located at depth beneath the surface and often beneath groundwater aquifers, it is important to avoid contamination of the groundwater by methane and other components of the coal seam or shale gas. This means that any wells drilled to extract the gas must be adequately sealed and isolated from the groundwater regime.

In order to protect these aquifers from potential contamination the following measures should be undertaken.

- It should be a requirement to demonstrate that coal or shale seams are not hydraulically connected to the overlying potable water aquifers. This will require a good understanding of the local and regional hydrogeology and normally this is only achieved after extensive geological and hydrogeological investigation of the well site and surrounding areas.
- If the use of hydraulic fracturing is anticipated to assist in gas recovery, then it should be a requirement to demonstrate that such fracturing will not connect the coal or shale beds

hydraulically to those overlying aquifers. Such a demonstration would first require sound knowledge of the local geology and hydrogeology. The extent of propagation of the hydraulic fractures would also need to be monitored using microseismic monitoring techniques (e.g., see King, 2012).

- The installation of multiple physical barriers, in the form of concentric layers of casing and cement should be mandatory to a depth that will extend the casing well through and below the bottom of the lowest aquifer. API (2009) recommends that this depth should be at least 22 metres (75 feet) below the bottom of the lowest aquifer to be protected. These barriers should be pressure tested before the well is put into production.
- If water is produced as part of the gas extraction, it should only be used to recharge the aquifers if it is first appropriately treated.

11.4 Coal seam water

Extraction of gas from a shale or coal seam often requires pumping and consequential extraction of groundwater. As indicated previously, this pumping may be necessary to reduce the pressure in the groundwater at the level of the coal seam in order to produce a pressure gradient between the gas bound to the coal and the natural or induced fracture system in the coal or shale. It is this pressure gradient that induces the gas to flow from the coal or shale towards the well. In such cases some water will be produced as part of the gas extraction process. Often this water will be saline, e.g., approximately 3000 to 7000 ppm (or mg/L) (NSW Office of Water, 2013), and it should be disposed of appropriately. By way of comparison, sea water is typically 24,000 ppm.

Evaporation of this saline water from surface storage ponds is not a particularly constructive use of that water. Alternatively, saline water can be desalinated in reverse osmosis or in ion exchange plants or else it may be pumped into suitable saline aquifers. The desalinated water can be used for agriculture or industry or pumped underground to recharge aquifers. Brine may also be used by industry or piped or otherwise transported to the coast for disposal into the sea, depending of course on the feasibility of these disposal options (e.g., Santos, Undated 1 & 2).

Clearly a water management plan is required as an essential component of any responsible gas extraction operation, regardless of whether horizontal drilling is employed in its development. The volume of water to be managed in this way will vary according to the scale of the operation and the local hydrogeological conditions. For example, unlike some other coal seam gas areas in Australia, the coal seams involved in the Camden Gas Project in NSW are considered to be relatively tight and therefore likely to produce relatively modest volumes of water. Indeed, the operator, AGL, claims that in the year ended 30 June 2012 a total of less than 4.8 megalitres of water was produced from its production wells (AGL, 2013a).

In general, mitigation strategies should also be developed for any unplanned water discharges or accidental spills.

11.5 Subsidence

Primarily because horizontal drilling for the extraction of coal seam gas is usually conducted at considerable depth below the surface and because the coal formations and overlying strata are reasonably competent rocks (at least in NSW), there is little potential for subsidence to occur as a result of the well drilling operation alone.

Subsequent extraction of the gas during production requires pumping of fluid (gas and some groundwater) from the ground. In principle, there is therefore some potential for the extraction of these fluids and the consequential reduction in fluid pressure locally in the coal seam to cause a reduction in the voids in the coal and possibly the overlying rock in the longer term. Theoretically, this could lead to some volume reduction in the formation, which might be manifest as surface subsidence. However, there is very strong evidence from the geology to suggest that this effect will be negligible in most cases. It would certainly be negligible (i.e., imperceptible) in most of the known coal measure rocks in NSW.

There is independent support for this contention. As part of the Stage 2 expansion proposal for the Camden Gas Project in NSW, AGL commissioned Mine Subsidence Engineering Consultants Pty Ltd (MSEC), to investigate the potential for the proposed CSG extraction to result in subsidence at the ground surface. In the report prepared by MSEC it was noted: "the proposed extraction of coal seam methane at Camden will not create large voids in the strata, nor leave remnant [coal] pillars. The strata within the coal measures are not unconsolidated and in fact are hard and well consolidated rocks. The conditions for significant subsidence to occur are not therefore present and it is concluded that the potential for subsidence to occur as the gas is extracted is almost negligible" (MSEC, 2007).

11.6 Induced seismicity

It is most unlikely that horizontal drilling alone, when used in CSG operations, will cause a significant microseismic event. However, at least in principle this may no longer be the case if hydraulic fracturing is used in conjunction with horizontal drilling. It is worth noting that most hydraulic fracturing conducted to date in NSW has been associated with vertical wells, rather than horizontal drilling, and most, if not all, horizontal wells bored to date in NSW coal seams have involved no hydraulic fracturing. So the evidence required to make this assessment with respect to NSW coal seam gas operations involving horizontal drilling is quite limited. Fortunately, studies conducted elsewhere in shale gas operations (e.g., National Research Council, 2012) provide some useful evidence on which to base reasonable, albeit perhaps tentative, conclusions for coal seam gas operations.

There are two readily identifiable types of seismicity normally associated with hydraulic fracturing. Microseismic events are a routine feature of hydraulic fracturing and are due to the propagation of engineered fractures through the rock. Larger seismic events are generally rare but, potentially, they could be induced by hydraulic fracturing, particularly if a pre-stressed geological fault is located close to the source of the hydraulic fracturing. This is of particular importance for CSG developments near urban centres (e.g., St. Peters in Sydney). CSG extraction using hydraulic fracturing needs to be carefully planned to minimise the risk of large seismic events. This should involve controlling the fluid injection rates used for fracturing throughout the CSG field and by optimising the placement of wells.

Usually, the microseismic events induced by hydraulic fracturing are small and can only be detected with very sensitive equipment. It is noted that the energy released during hydraulic fracturing is usually less than the energy released by the collapse of open voids in rock formations, as occurs during coal mining. Planes, trucks and many other human activities generate noise and ground vibrations that are often stronger and more frequent than the seismic events associated with most mines or CSG extraction (Beck, 2012). According to a recent study conducted by the National Academies in the USA "the process of hydraulic fracturing a well as presently implemented for shale gas recovery does not pose a high risk for inducing felt seismic events" (National Research Council, 2012).

11.7 Impacts and risks of other forms of horizontal drilling

It is important to realise that other forms of horizontal (or directional) drilling are not without impacts and risks associated with their use. In particular, it is worth mentioning briefly some of the impacts of the use of the method known as Horizontal Directional Drilling (HDD), described previously. It will be recalled that this is shallow directional drilling that usually takes place in the top 10 metres below the surface.

Murray et al. (2013) and Kruse (2009) indicated that the majority of HDD installations world-wide have been well managed and have been successful, but they also noted that there have been several cases where this method has lacked sufficient risk assessment and mitigation strategies to control the risks that are generally inherent in projects carried out below the ground.

Murray et al. (2013) identified twenty-one key risk events, which they categorized into risks occurring within the subsurface or at the surface. They included risks to both the environment and the overall project construction schedule (and hence the project cost), and provided a prioritization of these risk events on the basis of their analysis of data recorded on HDD projects located throughout Alberta and north-eastern British Columbia, Canada. Amongst the 16 sub-surface risks and impacts they identified a number with potentially serious environmental consequences, such as: hydraulic fracturing allowing drilling fluid to escapes the borehole and be released to the surface, subsequently requiring clean-up activities to be initiated; and the occurrence of a collapsing borehole, in which soft cohesive soils can squeeze into the borehole annulus or loose granular soils can fall into the borehole annulus producing an obstruction. Collapse (or partial collapse) of the hole is also likely to cause noticeable surface subsidence in these operations. Other risks with potentially significant impacts on other human activities include getting the drill string stuck in the hole. If the latter risk eventuates, surface excavation may ultimately be required to extract the drill string, and this is often likely to cause significant disturbance to human activity.

The continued success of HDD relies heavily on a clear understanding and effective management of the possible impacts and risks that may be encountered during construction. Equally important is the need to develop mitigation or control strategies if any of the identified risks events materialises. The need for such risk analysis and the development of mitigating strategies has been stated clearly and succinctly by Murray et al. (2013):

> "Risk assessment strategies serve to illuminate a prioritization of risks based on their likelihood of occurrence and impacts. Prioritized risks are dealt with through risk response strategies, which include avoidance, transfer, acceptance and mitigation. Mitigation is the best response to risk events with significant risk impacts to project objectives. … By understanding the threats to project objectives, the industry stakeholders can better determine their respective strategies for risk response providing successful project completion and capitalizing on opportunities to advance the technology."

These general comments also apply to horizontal drilling for unconventional gas.

11.8 Summary

It is important to emphasise again that many of the impacts of horizontal drilling activities for unconventional gas, as described in this section can be reduced, or potentially eliminated, if appropriate procedures and risk mitigation strategies are adopted. Ultimately, a formal environmental risk assessment will need to be performed for each particular development, considering the site-specific risks and the proposed mitigation strategies.

11.9 Comparison of the impacts of horizontal and vertical drilling for shale gas

As already noted, the extraction of unconventional gas from coal seams or shale formations often requires the use of unconventional drilling techniques. Primarily this means the use of horizontal drilling technology, perhaps in combination with hydraulic fracturing of the reservoir rocks. It is therefore instructive to make some comparisons of the two types of activity, viz., vertical well operations versus horizontal drilling, in terms of some of their impacts. One such comparison has been provided for the case of shale gas extraction in the Marcellus Shale, located in the north east of the USA (MOE, 2012).

The Marcellus Shale is an unconventional natural gas resource found beneath the surface of the states of Pennsylvania, Ohio, West Virginia, and New York. The natural gas found in the Marcellus Shale requires unconventional methods of extraction, including horizontal drilling and high-volume hydraulic fracturing, because of the way the natural gas is trapped in the geological formation. The Museum of the Earth (MOE) based in Ithaca, New York, has provided a comparison of some of the requirements and impacts of the unconventional horizontal drilling required to recover the unconventional gas, compared with those of more conventional vertical drilling. An extract from this comparison is reproduced in Table 1 below.

TABLE 1: COMPARISON BETWEEN VERTICAL AND HORIZONTAL DRILLING FOR SHALE GAS (MOE, 2012)

Well type	Vertical	Horizontal
Well pad footprint	>1 acre to 3 acres	3 to 6 acres
Road construction footprint	Similar to unconventional drilling	5.7 acres
Water required	20,000 to 80,000 gallons	2 to 9 million gallons; average 4 million gallons
Time to drill well	~ 1 month	~ 3 months
Hydraulic fracturing required	Sometimes	Almost always

In particular, experience in the Marcellus shale has shown that vertical wells typically use 20,000 to 80,000 (US) gallons of water for hydraulic fracturing. However, experience has also shown that horizontal wells require between 2 and 9 million gallons of water for hydraulic fracturing (MOE, 2012).

From these example data it can be concluded that vertical well operations may differ from horizontal well drilling operations in terms of the scale of the operation. In the case of the Marcellus Shale operation, and according to the Museum of the Earth, each horizontal well site requires much more water and more surface space, and a longer drilling time than a conventional vertical well development. More water is required largely because of greater drilling lengths and significantly more hydraulic fracturing. More surface space reflects the need for more complex equipment, and the longer drilling time is simply a function of the greater drilling lengths and the probability of drilling multiple horizontal boreholes from the one drill pad. However, it should also be noted that the lateral 'reach' within the reservoir of horizontal drilling far exceeds that of a single vertical well, so that generally in the case of horizontal drilling fewer wells and surface pads are required to recover gas from a reservoir of large lateral extent. As indicated previously, in terms of production area it is not unreasonable to consider one horizontal well as the equivalent of approximately 25 vertical wells. Thus overall, it is reasonable to expect that the unconventional operation should have a smaller overall surface footprint.

As noted by AGL (2013b), there has been limited horizontal drilling to date in the existing coal seam gas operations in NSW. Thus, at present there is only limited data available in the public domain from which to draw comparative conclusions, such as those that have been suggested for the Marcellus shale gas operations. In general, coal seams have much higher natural permeability than tight shale formations, and so the amount and extent of hydraulic fracturing (and the amount of water required) is likely to be significantly reduced in the case of coal, for the same volume of extracted gas. However, it is suggested that radical departure from the broad conclusions suggested by MOE, at least with regard to the relative impacts and scale of the two types of drilling operations, is unlikely.

12 WORST CASE SCENARIOS

As some engaged in the public debate over CSG have opined "Opposition to coal seam gas [is] based on worst-case scenarios" (MacDonald, 2012). It is therefore worth examining what might be meant by the term 'worst case scenarios', especially in the context of horizontal drilling as used in CSG operations.

As noted by Dr Philip Pells (as reported by Cox, 2013), there is no universal worst case scenario for the coal seam gas industry. What constitutes the 'worst case' will depend very much on the specific site being considered. The local geology and in particular the local hydrogeology will be important, and in some cases perhaps the controlling factors, in what constitutes the worst case scenario.

Possible 'worst case' scenarios include the following:

- Fracturing of the coal seam unintentionally causing a hydraulic connection between the coal seam and the overlying fresh water aquifers, leading to contamination of those aquifers. This situation would be unlikely for deep coal seams with significant thickness of aquitard(s) between the coal and the fresh water aquifer. The risk of this scenario occurring is higher for relatively shallow coal seams with aquitards of limited thickness, or indeed no aquitard between the coal and the fresh water aquifer. Fracturing should normally not be permitted in the latter case unless it can be demonstrated that the risk can be adequately mitigated or avoided.
- Microseismicity associated with hydraulic fracturing affecting well integrity. This risk can usually be controlled with appropriate choice of the fracture initiation points.
- Leakage due to poor well integrity, e.g., imperfect well casing. A means of detecting such leaks is required, highlighting the need for a comprehensive well monitoring system to be put in place, supplemented by regular monitoring and testing of the groundwater.
- Well blowout. There are industry standard methods to mitigate against this possibility.

The risk of an occurrence of any of these scenarios should be assessed on a site-specific basis. With appropriate planning and control measures in place, it is possible to mitigate against each of these 'worst case' scenarios and a number of these control measures have already been discussed. A properly constructed well bore is one of the key mitigation strategies. Nevertheless, plans should always be put in place to deal with any of these scenarios, should they occur. Some of the more significant risks have been addressed previously in Section 8, while some of the 'best practice' strategies to mitigate these risks have been described in Section 9.

13 KNOWLEDGE GAPS

Horizontal drilling is now considered to be a relatively mature technology as a consequence of the numerous advances that have occurred since it was first developed for oil recovery in the 1970s.

Clearly, it is possible that the technology may continue to improve and become more efficient in the future, but there would seem to be few if any major gaps in current knowledge of the drilling process itself.

However, there are certainly identifiable gaps in our knowledge of the safe and reliable application of this technology to the extraction of coal seam gas, particularly if horizontal wells are used in conjunction with hydraulic fracturing. The major areas of uncertainty relate to the hydrogeology of the CSG site, the potential for accidents and their management, the management of water that is produced by CSG operations, the potential effects on human health of CSG operations, the lack of surveys of background levels of various chemicals associated with CSG, and the lack of publicly available results of ground water modelling. These are described further in this section.

13.1 Hydrogeology

Probably the major source of current uncertainty lies in our lack of detailed knowledge of the hydrogeology of many potential sites for coal seam gas recovery. Indeed, the hydrogeology at each specific site will be unique and it is likely to be the most significant unknown for most greenfield developments. Furthermore, the time for gas extraction to have a significant impact on the groundwater can be long, perhaps even decades or more, so that once a problem is detected it could be too late to do anything to rectify the problem. Thus there is the potential for the short-term benefits of gas production obtained by one generation to have long-lasting impacts on future generations (Kelly, 2011).

CSG production can be carried out with minimum impact on adjacent groundwater systems provided the appropriate precautions are taken, some of which have been described previously. But as for any complex operation there is always a risk that an accident will happen. If it does happen, the obvious question is what will be the impact? Research is required in order to answer such questions. Some of the answers will be quite general and may apply in almost all situations. However, others will be distinctly site specific. It is this site-specific nature of some of the risks and their consequences that requires detailed study, prior to gas production getting underway.

13.2 Water management

Some CSG operations are likely to produce relatively large quantities of water extracted from the coal seams. How the operators of such activities will manage the potential large volumes of poor quality saline water they will bring to the surface requires detailed investigation. Clearly, the solution should be presented before the CSG operation commences. It should not be a work in progress.

13.3 Background surveys

Background surveys, to quantify the natural level of organic compounds (including methane) in the aquifers of interest, should be conducted routinely on each CSG project. Without background surveys, it is not possible to know if the levels have been affected by CSG production. Obviously, it is imperative to be able to separate the impact of CSG production from natural background levels. It is not clear whether such background surveys have been conducted on all existing CSG operations in Australia, but it would certainly be prudent for them to be conducted on all future projects of this type.

According to Kelly (2013), research from the USA has suggested that methane contamination of groundwater can occur up to one kilometre away from gas production sites. Others, e.g., King (2012), have suggested that such contamination is likely to be associated with poor well construction, particularly poor isolation of the well during the well construction phase, in "many, if not all" cases (p. 67 of King, 2012). However, it is important to note that the occurrence of such contamination depends significantly on the local geology, the borehole installation procedures and method of operation. It may be possible to avoid such contamination if appropriate best practice procedures are adopted.

13.4 Health issues

Community concerns over unconventional gas production in Australia are increasing. These concerns relate mostly to water and air pollution, land usage, fugitive emissions and whether the level of assessment and regulation is appropriate. Potentially, some of the environmental impacts may have serious consequences for human health. All of these issues require further research.

According to Shearman (2012): "The fundamental public health issue is the potential for water contamination by chemicals which could seriously affect human health decades after exposure. Health impacts may arise from the use of fracking chemicals or from the release of hydrocarbons and other contaminants from the coal seams. … Pollutants – particularly volatile organic compounds – may [also] be released into the air at the well head."

Some of the concerns expressed publicly are specifically related to hydraulic fracturing and the chemical compounds that may be used in carrying out these operations, particularly the so-called BTEX compounds (the chemicals benzene, toluene, ethylbenzene and xylene). It is important to note that the use of BTEX compounds in hydraulic fracturing is banned in NSW. Nevertheless, some commentators claim that there has been no comprehensive hazard assessment of the chemical mixtures used in hydraulic fracturing, their impacts on the environment or human health, and the cumulative effects of exposure, as well as no comprehensive environmental monitoring and health impact assessment (e.g., Lloyd-Smith and Senjen, 2011). It is also claimed that many of the chemical risks associated with CSG and hydraulic fracturing are not comprehensively assessed.

If these public concerns are to be adequately addressed, further research will be required. This should probably include studies of air emissions from evaporative ponds (which are also banned in NSW) and emissions and releases from gas flares and pits, as well as the endocrine disrupting potential of any compounds released during CSG operations. These studies should aim to quantify the level of emissions as well as their potential to affect human health. It is understood that some work of this type is currently underway (IESC, 2013).

13.5 Modelling

As previously noted, in regions where the rock formations between the deep coal seams and the overlying alluvial aquifers have few joints or faults, and have low permeability, it is unlikely CSG production will have any significant impact on the shallow alluvial aquifers. However, this likelihood needs to be tested and verified. One means of doing so involves both numerical modelling (simulation) and field observations.

There appears to be a distinct lack of results in the public domain of any specific three-dimensional flow simulations, particularly where the simulations have attempted to quantify the migration of fluids from the proposed CSG production zones to the fresh water aquifers used in irrigation or water supply. As observed by Kelly (2011): "There has [also] been a lack of good information provided to the general public to help them understand and visualise the impacts of CSG production. To inform the debate about the expansion of the CSG sector, 3D geological models and 3D flow simulation results need to be made publicly available."

The research that is required to increase public confidence in CSG activities is complex and likely to be quite costly, perhaps costing millions of dollars. It will be largely site-specific and it will also take several years if it is to be done correctly. As noted by Kelly: "Installing monitoring boreholes, running chemical tests and building 3D flow simulation models are all expensive activities. … That said, these studies are needed now before the sector gets too large."

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APPENDIX A – TERMS OF REFERENCE FOR THE BACKGROUND PAPER ON HORIZONTAL DRILLING

To deliver a Background Paper to the Office of the NSW Chief Scientist and Engineer (OCSE) providing information and a discussion about horizontal drilling in the context of coal seam gas (CSG) activities.

1. The Background Paper should be 50 pages maximum length (excluding appendices). The Background Paper must be delivered electronically in Word format; be fully referenced and contain suggestions for further reading for those interested in gaining a more detailed understanding of the subject.
2. The purpose of this background paper is to provide an overview of horizontal drilling in the context of CSG, and in doing so, to communicate and contextualise potential risks from horizontal drilling.
3. The Background Paper should include discussion of the following:
   a) What is horizontal drilling?
   b) What are the applications of horizontal drilling? E.g. mining, CSG, public utilities such as water and gas pipes etc.
   c) History of horizontal drilling use for unconventional gas with a focus on Australia. (to extent possible)
   d) Methodology and processes - How horizontal drilling is conducted for unconventional gas? Please comment on best practice methodologies. (to extent possible)
   e) In what situations is horizontal drilling used in unconventional gas production (include a discussion of CSG and shale gas)? This should note the differences between horizontal drilling, vertical drilling and hydraulic fracturing, including the situations (e.g. geological, financial, environmental) that each are used in (separately or combination).
   f) Are there potential negative impacts that could occur from horizontal drilling in unconventional gas extraction, such as subsidence, induced seismicity or other issues? What risk assessment and risk management approaches are there to manage horizontal drilling so as to minimise negative impacts.
   g) Are there potential negative impacts that could occur from horizontal drilling of other applications as set out in b (above), such as subsidence, induced seismicity or other issues?
   h) What are the possible worst case scenarios, and what are the likelihoods of these scenarios? (to extent possible)
   i) What are the knowledge gaps/unknowns/research questions, of relevance to CSG, in relation to horizontal drilling?
   - The Background Paper should be developed having regard to the following:
   a) Under Terms of Reference 6 of the Review (Schedule D), a series of information papers will be commissioned about the CSG industry; which are aimed at informing the Review and a wide audience, both general and technical. These information papers are likely to be publicly released and may appear on the website of the Chief Scientist and Engineer.
   b) Each Review information paper will draw on multiple sources of information, including background papers which may be sourced from different experts.
   c) The Review information papers are likely to include extracts from the expert background papers, including the Background Paper delivered under this contract. In some cases, a background paper may be appended to a Review information paper in part or full, and therefore may be publicly released and may appear on the website of the Chief Scientist and Engineer.

APPENDIX B – ACRONYMS

Abbreviation	**Definition**
API	American Petroleum Institute
AGL	AGL Energy Limited
BTEX	Refers to the chemicals benzene, toluene, ethylbenzene and xylene
CBM	Coalbed methane
CSG	Coal seam gas
CSIRO	Commonwealth Scientific and Industrial Research Organisation
HDD	Horizontal directional drilling
HID	Horizontal in-seam drilling
MSEC	Mine Subsidence Engineering Consultants Pty Ltd.
ODD	Oilfield directional drilling

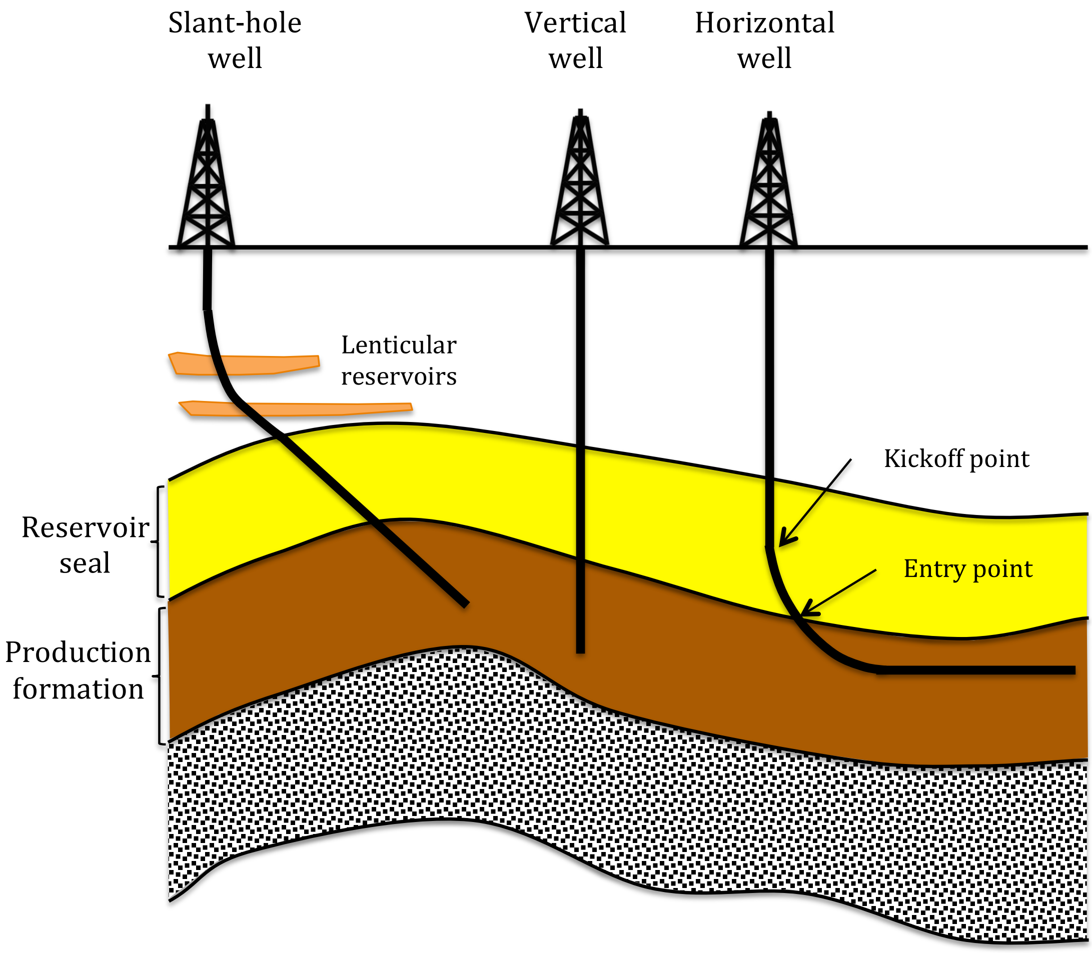
APPENDIX C – GLOSSARY

(After Royal Society, 2012 and others)

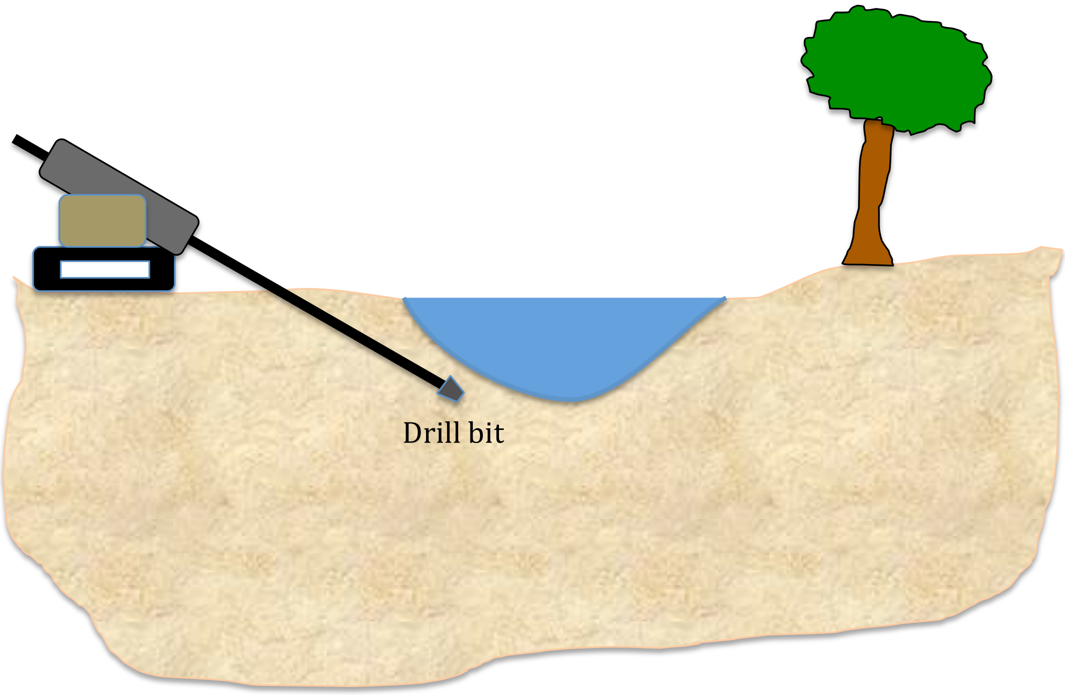
Term	Definition
Adsorption	The adhesion of atoms, ions, or molecules from a gas, liquid, or dissolved solid to another solid surface.
Aquitard	A soil or rock formation whose permeability is so low it cannot transmit any useful amount of water.
Blowout	A sudden and uncontrolled escape of fluids from a well up to the surface.
Blowout preventer	High pressure wellhead valves, designed to shut off the uncontrolled flow of hydrocarbons.
Borehole	See 'wellbore'.
Cap rock	A layer of relatively impermeable rock overlying an oil- or gas-bearing rock.
Casing	Metal pipe inserted into a wellbore and cemented in place to protect both subsurface formations and the wellbore.
Christmas tree	Also known as a wellhead.
Cement bond log	A method of testing the integrity of cement used in the construction of the well, especially whether the cement is adhering effectively to both sides of the annulus between casings or between the outer casing and the rock sides.
Coal bed methane	A form of natural gas found along with coal seams underground.
Conventional gas	Hydrocarbons in the form of gas that is trapped in rock structures caused by folding and/or faulting of sedimentary layers.
Cleats	Open fracture system in coal seams.
Directional drilling	The intentional deviation of a wellbore from the path it would naturally take.
Disposal well	A well, sometimes a depleted oil or gas well, into which waste fluids can be injected for safe disposal.
Drilling mud	Drilling fluid circulated to the bottom of the borehole and used to keep the drill bit cool and clean during drilling, and to suspend the drill cuttings, usually returning them to the ground surface.
Flowback water	The fluid that flows back to the surface following a fracturing treatment. It is a mixture of the original fracturing fluid and saline water containing dissolved minerals from the rock formation.
Fracking or fraccing	The process of creating cracks in underground coal seams or other rock formations to increase the flow and recovery of gas out of a well.
Fugitive emissions	Emissions of gases or vapours from pressurized equipment or coal seams due to leaks and other unintended or irregular releases of gases.
Groundwater	Water found beneath the earth's surface.
Hazard	A hazard is something (e.g. an object, a property of a substance, a phenomenon or an activity) that can cause adverse effects.
Horizontal drilling	A special case of directional drilling where the well is deviated onto a horizontal plane.
Hydraulic fracturing	A means of increasing the flow of oil or gas from a rock formation by pumping fluid at high pressure into the well, causing fractures to open in the formation and increase its permeability.
Hydrogeology	The geology of groundwater, especially concerning the physical, biological and chemical properties of its occurrence and movement.
Leakoff test	A test used to determine the pressure required to initiate fracturing of the rock formation.
Microseismicity	Very small seismic events, normally below -1.5 ML.
Natural gas	The term applied to a combustible mixture of hydrocarbon gases trapped underground in rock formations.

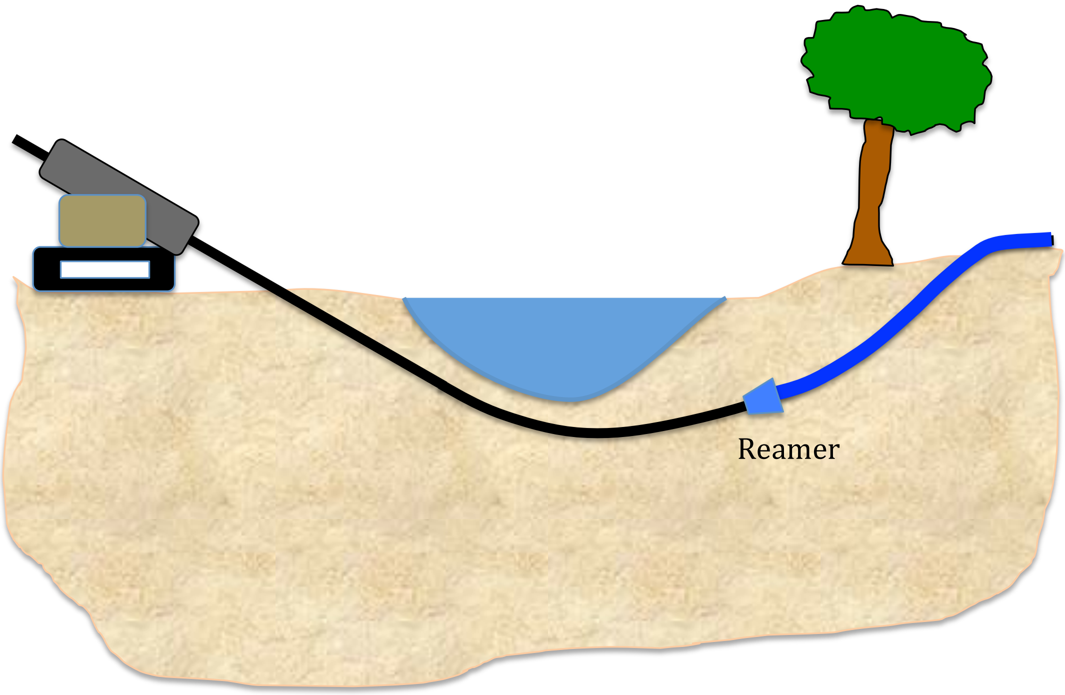
Pad-based drilling	The process of drilling multiple wells from the same surface drill pad.
Permeability	A measure of the ability of a rock to transmit fluid through pore spaces.
Porosity	A ratio between the volume of the pore space in reservoir rock and the total bulk volume of the rock. The pore space determines the amount of space available for fluids.
Pressure test	A method of testing well integrity by raising the internal pressure of the well up to maximum expected design parameters.
Produced water	The fluid that returns to the surface during the production phase of a well that contains both fracturing fluid and saline water from the rock formation.
Proppant	Particles (normally sand) mixed with fracturing fluid to hold fractures open after a hydraulic fracturing treatment.
Proved reserves	The volume of technically recoverable resources demonstrated to be economically and legally producible.
Reservoir	A subsurface body of rock that acts as a store for hydrocarbons.
Risk	A risk is the likelihood that a hazard will actually cause its adverse effects, together with a measure of the effect.
Seismicity	Sudden geological phenomena that release energy in the form of vibrations that travel through the earth as compression (primary) or shear (secondary) waves.
Seismic reflection surveys	A technique that uses reflected seismic waves to map the structure of rock layers in two- or three-dimensions.
Surfactant	A chemical that lowers the surface tension or interfacial tension between fluids or between a fluid and a solid.
Sweet spot	Regions in oil and gas reservoirs with high concentrations of hydrocarbons that are most amenable to production.
Technically recoverable resource	The volume of gas within a formation considered to be recoverable with existing technology.
Thermogenic methane	Methane produced by the alteration of organic matter under high temperatures and pressures over long time periods.
Tiltmeter	An instrument used to detect microdeformations in surrounding rock.
Tracer	A chemical additive that can be used to identify the presence of the fracturing fluid by subsequent monitoring.
Unconventional gas	Hydrocarbons in the form of gas found in a reservoir of low or zero permeability.
Wellbore	The hole created by drilling operations, also known as the ‘borehole’.
Wellhead	The component at the surface of an oil or gas well that provides the structural and pressure-containing interface for the drilling and production equipment.
Well integrity	The ability of the well to prevent hydrocarbons or operational fluids leaking into the surrounding environment.
Well pad	The surface infrastructure of the drilling operations.

FIGURES



BACKGROUND PAPER ON HORIZONTAL DRILLING
SCHEMATIC ILLUSTRATIONS OF OILFIELD DIRECTIONAL DRILLING





BACKGROUND PAPER ON HORIZONTAL DRILLING
SCHEMATIC ILLUSTRATION OF HORIZONTAL DIRECTIONAL DRILLING

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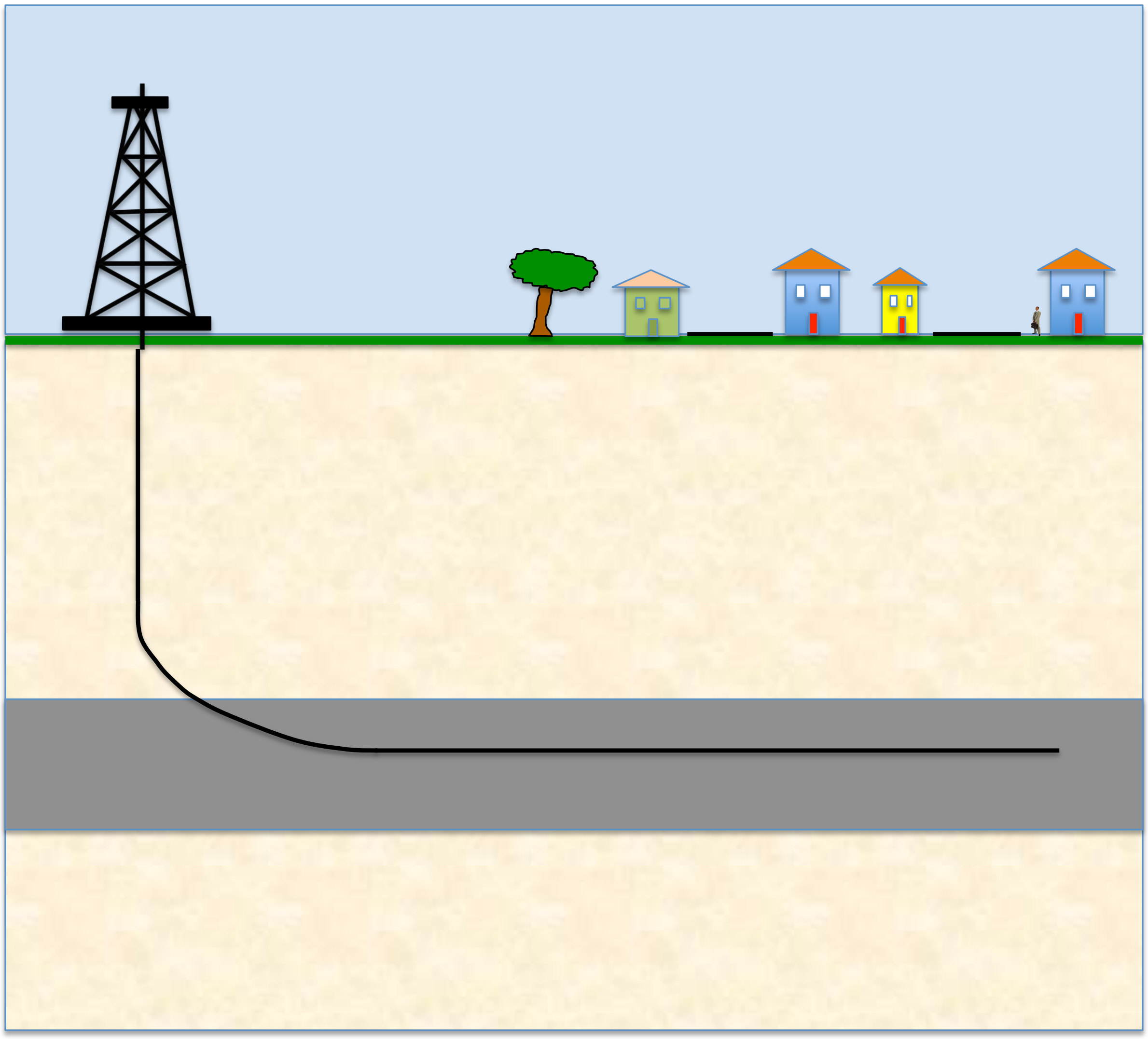
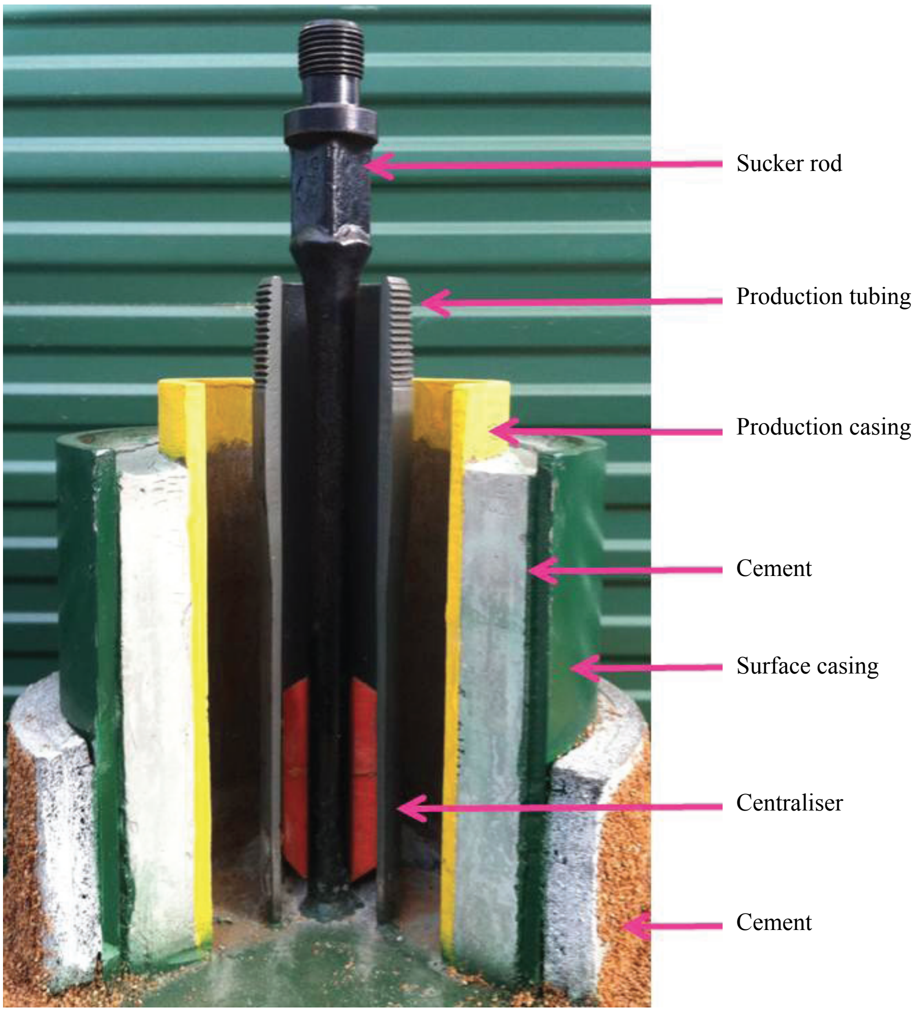
Source: http://upload.wikimedia.org/wikipedia/commons/3/3f/Horizontal_Drilling_1.JPG

BACKGROUND PAPER ON HORIZONTAL DRILLING
TYPICAL EQUIPMENT USED IN HORIZONTAL DIRECTIONAL DRILLING

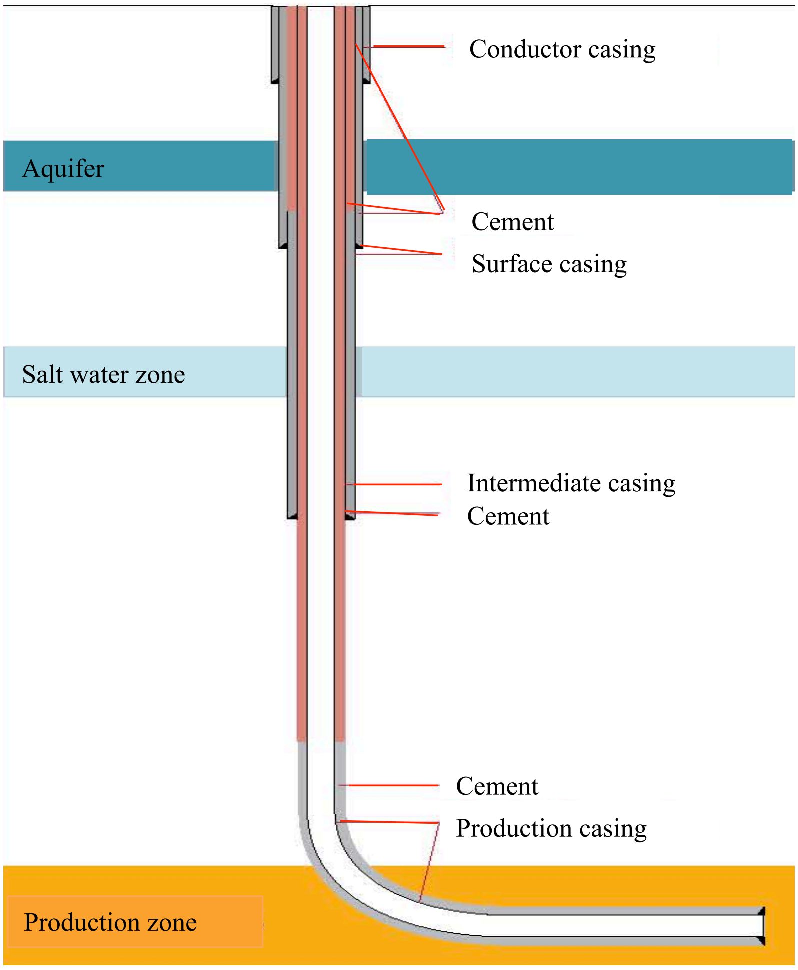


BACKGROUND PAPER ON HORIZONTAL DRILLING
SCHEMATIC ILLUSTRATION OF IN-SEAM HORIZONTAL DRILLING



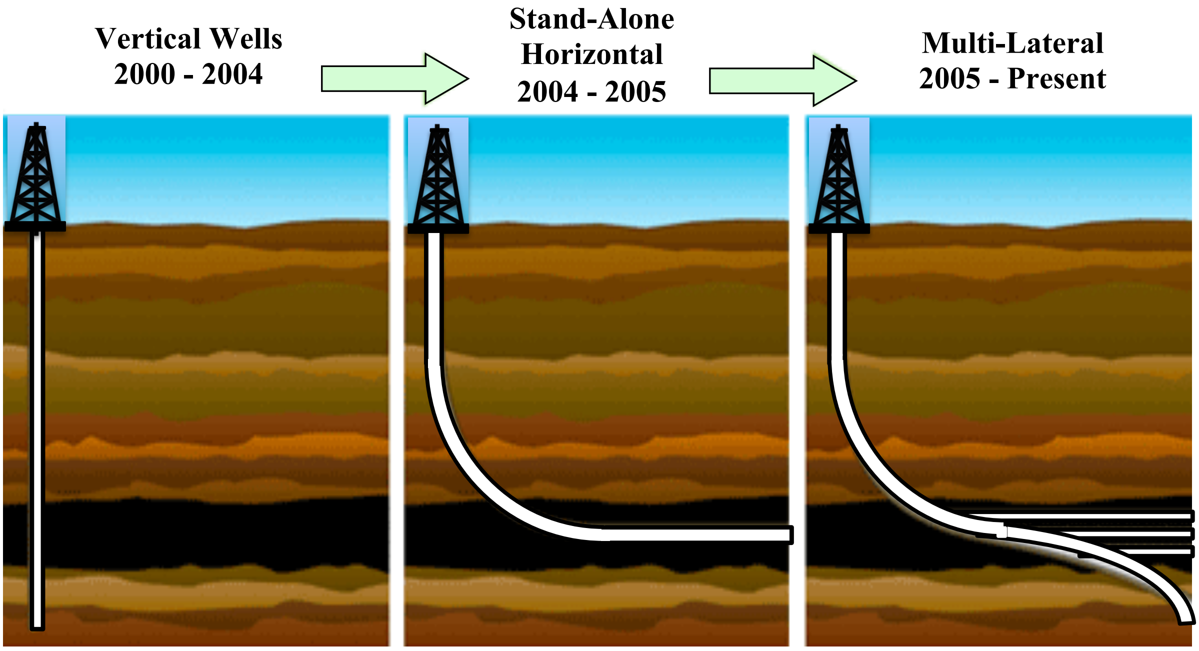
Source: http://agk.com.au/camden/assets/pdf/Jan2013/130122_FracturingFactSheet.pdf

BACKGROUND PAPER ON HORIZONTAL DRILLING
SECTION OF A WELLBORE AS USED BY AGL, SHOWING ITS 4 BARRIERS



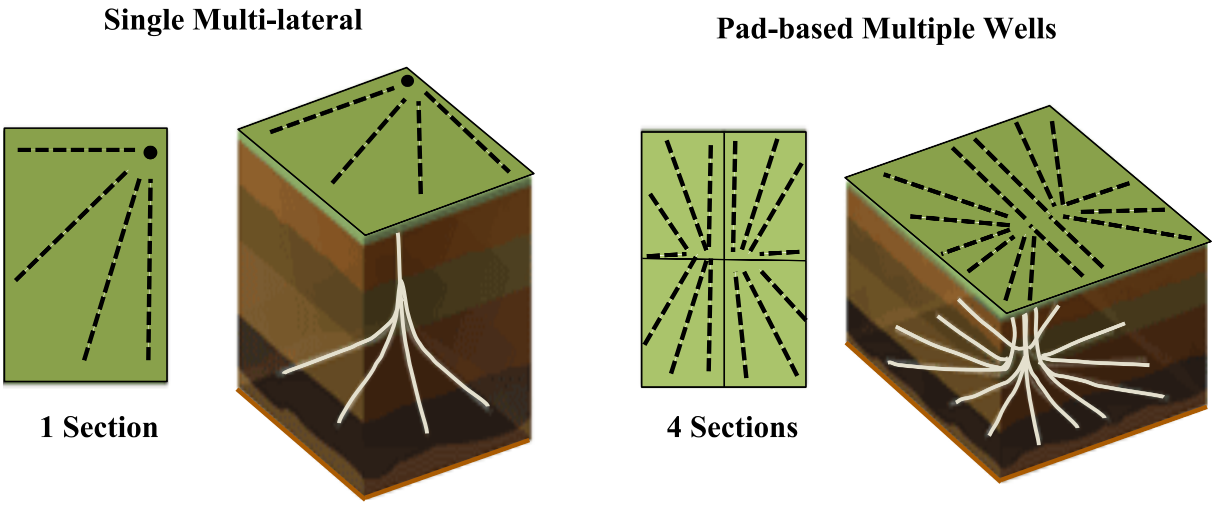
Source: After Royal Society (2012)

BACKGROUND PAPER ON HORIZONTAL DRILLING
ILLUSTRATION OF THE STAGES OF CASING FOR A HORIZONTAL WELL IN A SHALE GAS OPERATION (Royal Society, 2012)



Source: After http://www.trident4-22.ca/index.php?page=pad-based-drilling

BACKGROUND PAPER ON HORIZONTAL DRILLING
ILLUSTRATION OF VERTICAL AND HORIZONTAL WELLS



Source: After http://www.trident4-22.ca/index.php?page=pad-based-drilling

BACKGROUND PAPER ON HORIZONTAL DRILLING
ILLUSTRATION OF PAD-BASED DRILLING