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Underground coal gasification: issues in commercialisation

Leonard Keith Walker BE, MBA, PhD (Cantab), FAusIMM
Executive Chairman, Ascot Energy Ltd, Melbourne, Victoria, Australia

Back in 2007, it was expected that commercial gas production from underground coal gasification (UCG) technology would be in progress within the following 5 years. This has not occurred, particularly in Australia, where at the time three commercial projects were being aggressively pursued. This paper reviews each of five key issues that may be considered to have delayed UCG commercialisation. Of these, it is concluded that the primary factor is the use of government environmental policy to achieve its preferred energy outcomes, as in the development of the coal seam gas industry in Australia. It is concluded that the UCG industry must select appropriate markets and utilise small-scale financially viable projects to achieve its required commercial breakthrough.

1. Introduction

Commercial development of the process of underground coal gasification (UCG) has been promoted as being imminent for many years. In November 2007 the author summarised the development history of the technology at that time, discussed relevant technical, environmental and commercial issues, and concluded with the opinion that 'commercial UCG gas production from a number of projects will be in progress within the next five years' (Walker, 2007).

It is evident that this outcome has not occurred. In fact, in some respects, the prospect for commercialising the technology has receded rather than advanced, despite a current wide acceptance that UCG is a 'clean coal technology of the future'. In Australia, the Queensland government has adopted the recommendation of an advisory panel that '…until decommissioning has been demonstrated …no commercial facility should be commenced' (DEHP, 2013). In South Africa, the next stage of development of the Eskom project is dependent on the granting of permits and licences (Eskom, 2013) and, while there is publication of other prospective projects in many countries, no gas is currently being produced from any of them, even at the pilot scale.

It is instructive to review events that have occurred in the UCG field over the past 5 years to evaluate those factors that may have restrained commercial development of the technology and to reassess prospects for its commercial development in the near future.

The main factors relevant to commercialisation can be considered under a number of headings although, realistically, there is significant overlap between them. These factors are

- demand
- technology
- financial issues
- environmental issues
- political issues.

For the purpose of this discussion 'commercial scale' is considered to involve the production of sufficient gas to supply the fuel for a nominal 100 MW open cycle gas turbine, an energy demand of approximately 10 PJ/year. This energy demand would be met by a UCG gas output of 2×10^9 m^3/year with a calorific value of 5 MJ/m^3 (assuming air injection), utilising approximately 1 Mt of coal per annum, depending on the coal energy value. This low calorific value means that the mass flow into a gas turbine is much greater than that using natural gas, which in turn increases the power output for integrated gasification combined cycle applications when compared to natural gas applications (Walker *et al.*, 2001). Due to the continuous nature of the UCG process, the syngas produced is best suited to base load applications.

2. Demand

Internationally, the demand for low-cost energy sources has only increased over the past years, with rising energy costs (Australian Financial Review, 2004) resulting from reduced supplies of natural gas in many countries (with the notable current exception of shale gas in the USA) and pressure building against the construction of conventional coal-fired power plants (USA Today, 2013). With low-cost syngas as a product and the potential for multiple end uses, UCG offers perhaps an even more attractive energy option now than it did 5 years ago.

To support the potential for the technology, there are vast coal resources in many countries that are too deep for potential open cut mining and uneconomic for underground mining, but are likely to be accessible using UCG technology (https://ascotenergy.com.au/). While the focus in Europe and the UK is on deeper coal (more than, say, 500 m, and potentially offshore), in many countries in the Asian region where gas supplies are restricted and power shortages are present, substantial coal resources may be accessed at much shallower depths.

Two such examples exist in Indonesia and Pakistan. In Indonesia, coal resources estimated at more than 100 billion tonnes have been identified on the islands of Sumatra and Kalimantan (ICMA, 2009) yet, on most coal deposits, drilling deeper than 150 m has seldom been undertaken, despite geological evidence that coal seams dip to much greater depths. In Pakistan, the vast Thar coalfield is estimated to contain more than 150 billion tonnes of coal (TCEB, 2014), most of which lies undeveloped at depths exceeding 150 m. These two countries are examples of locations where low-cost gas, specifically for power generation, would have a great impact on regional development. With current natural gas prices in many countries reaching levels of US$8/GJ and the cost of syngas production in the range US$2·50–3·00/GJ, the benefits of developing UCG gas as a supplement to natural gas supplies is evident.

Furthermore, in both countries, the demand for power has led to prices that could support a small-scale power plant (less than 50 MW) using low-cost UCG syngas, whereas conventional coal-fired power plants would be uneconomical at this scale. In Indonesia, for example, power is produced in relatively remote locations using diesel fuel at a cost of US$0·25–0·30/kWh, whereas a small syngas-fuelled power plant would be economic at less than half this price.

3. Technology

Of the five factors under review, the role of technology issues in restraining commercialisation of the UCG process is, in the author's opinion, of minimal significance. There are two key aspects relevant to forming this view – the capability of producing gas from a given coal deposit and the capability of expanding this gas production to commercial scale.

The capability of UCG technology to produce suitable gas for power generation has been amply demonstrated in projects of various sizes in countries as diverse as the former Soviet Union, the USA, Spain, Australia, South Africa, Canada and New Zealand, over a time period from the 1960s to the present (Walker, 2007).

From a number of publications (Burton *et al.*, 2006; Kreinin, 1992) and personal knowledge, the author estimates that production of gas using the UCG process has consumed

- 15 Mt of coal from five sites in the former Soviet Union
- 70 000 t of coal from 39 tests at 12 sites in the USA
- in excess of 100 000 t of coal from sites in other countries, principally Australia and South Africa.

Since 2000, three sites have produced gas in Australia (of which the Chinchilla plant operated from December 1999 to late 2013), one in New Zealand, one in South Africa (continuous since January 2007) and at least one reported each in China and Canada. The range of gas compositions obtained from past UCG trials is summarised in Figure 1, showing the influence of using air or oxygen to promote the process underground. These data give confidence that the UCG process can be applied to produce usable syngas from a wide range of coals in different countries with varying operating conditions. In addition, the data show that increased oxygen injected into the system produces higher concentrations of carbon monoxide and hydrogen, which are the building blocks for conversion of syngas to value-added petrochemical products.

However, apart from the particular remaining project at the Angren site in the former Soviet Union (now Uzbekistan), all of these projects have been at a non-commercial scale, either as demonstration pilot projects or as the first stage of proposed commercial projects that have yet to proceed. The three projects in Australia and the one in South Africa were all started with the intent of developing commercial projects, but none has gained approval for advancement at the time of writing (DEHP, 2012; Eskom, 2013). The expansion of gas production to commercial scale cannot of course be established until such approvals are given. The restraint on commercialisation would thus appear to relate more to the approval process than to technical aspects, as discussed in later sections.

The issue of the use of syngas produced from UCG operations in commercial gas turbines, such as manufactured by General Electric (GE), has been the subject of detailed review, with Walker *et al.* (2001) stating (with reference to gas produced at the Chinchilla, Queensland site) that 'GE has evaluated the syngas produced by the UCG facility in Chinchilla and has determined that it is an acceptable fuel for GE's syngas frame 6B heavy duty industrial gas turbine.' Variations in gas composition between sites will occur, which can be handled by variations in the design of appropriate gas clean-up plant to ensure that the syngas produced is acceptable to the gas turbine.

4. Financial issues

The two key interrelated financial aspects associated with the commercial development of UCG technology are funding for project development and the economic viability of a commercial UCG project.

While no commercial projects have been developed in the western world, ample funding over the past 10 years has been provided for preliminary project establishment in a number of

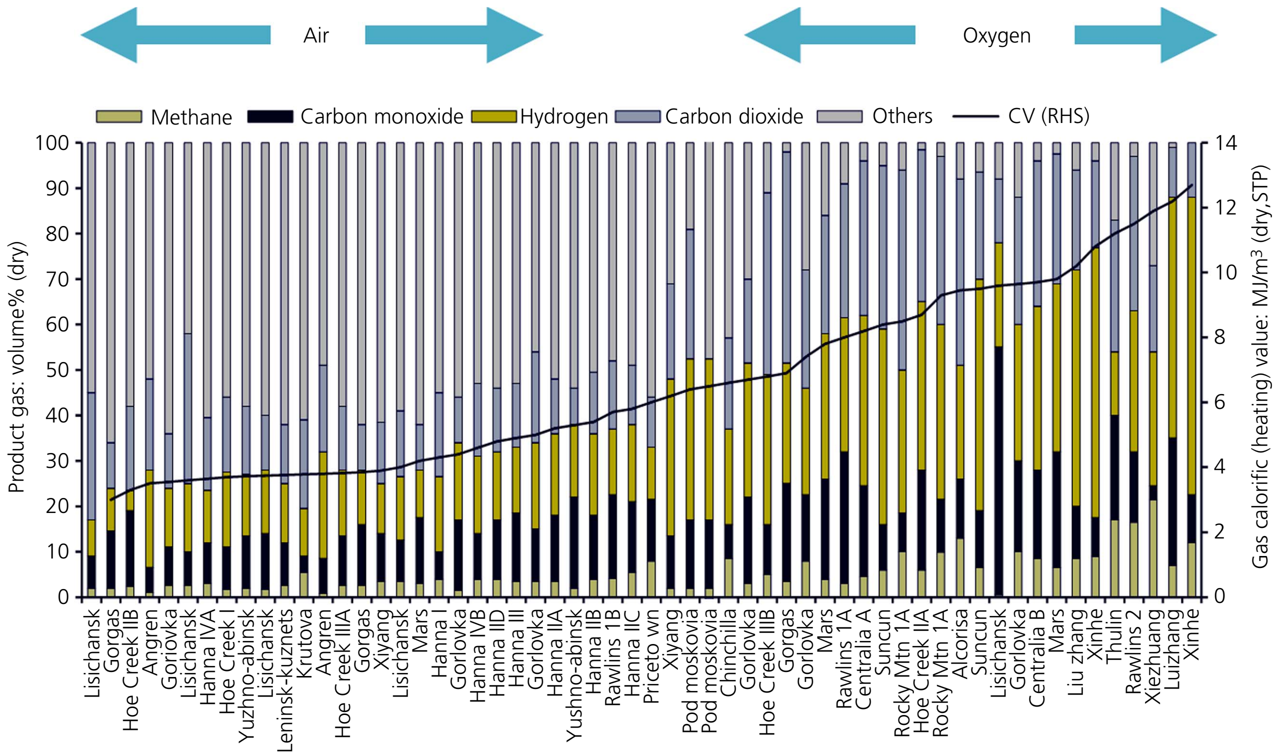

Figure 1. UCG product gas compositions

countries. In Australia alone, the author has estimated from published accounts of the three active companies (Linc Energy, Carbon Energy and Cougar Energy (renamed Moreton Resources Ltd.)) that approximately A$400 million has been invested in the establishment of gas production (all three sites), demonstrations of gas conversion to liquid fuel (Linc Energy) and small-scale power production (Carbon Energy). It is thus evident that investors in both large companies (Eskom in South Africa and Solid Energy in New Zealand) and small companies (in Australia) have sufficient confidence in the long-term future of the technology to support its development.

This support is backed up by published estimates of commercial project viability. In relation to power generation, Walker *et al.* (2001) estimated that the cost of electricity generation (including capital) was $US17/MWh for 70 MW of output and US$15/MWh for 280 MW of output. More recently, Ergo Exergy (Blinderman *et al.*, 2011) estimated power generation costs (again including capital costs) at approximately US$30/MWh for an output of about 300 MW. These cost estimates are considered to be reasonably consistent given the effect of inflation with the passage of time. Also in 2011, Carbon Energy estimated the cash cost (excluding capital) of power production at about US$15/MWh for a plant size of 300 MW, which could realistically be doubled if the cost of capital were to be included (Carbon Energy, 2011).

The author evaluated current power generation costs, inclusive of capital, for outputs of 200 MW (large scale for urban consumption, using a combined cycle gas turbine system) and 30 MW (small scale for remote consumption, using gas engines). The financial returns for realistic Asian power prices obtained following a range of enquiries by the author in Indonesia and Mongolia are summarised in Table 1. All capital and operating costs related to UCG gas production are included. The cost of power production is estimated to be approximately US$45/MWh for the large-scale plant and US$60/MWh for the small-scale power plant.

This information gives confidence that a commercial-scale UCG project should give attractive financial returns to investors, especially at a time when the costs of alternative energy supplies such as natural gas are escalating. The funding decision for larger scale projects, especially for the debt component, is constrained by the lack of a precedent of a current commercial UCG project and the consequent raising of the investment risk profile. This particularly applies to more complex end uses such as conversion of UCG syngas to liquid products, where significant additional process complexities are introduced, including the greater degree of control required over the product gas composition. It is the author's view that this can only be overcome progressively by starting with the

Nominal plant capacity: MW	Estimated capital cost: US$ million	Power price: c/kWh	Annual revenue: US$ million	Annual operating cost: US$ million	Net annual revenue: US$ million	Pre-tax internal rate of return 60/40 debt/equity: %
30	50	8	16	7	9	22
200	420	6	100	25	75	25

Table 1. Power generation: financial returns

construction of a phased power project at smaller scale, financed initially largely by equity alone, with the use of supporting debt for expansion as progress is achieved. There are, fortunately, ample locations where such a project could be developed and be financially viable, one example being remote areas in Indonesia that currently rely on expensive diesel fuel.

5. Environmental issues

5.1 Background

The author has previously summarised the environmental advantages of the UCG process in providing a syngas fuel source for a variety of applications and also detailed a number of environmental and social issues requiring attention as part of planning for a commercial UCG project (Walker, 2007). Of these, the most significant is the potential for groundwater contamination by the chemicals created by the gasification process. From a technical perspective, this potential is managed by maintaining a pressure in the gasification chamber lower than the groundwater pressure at the same level to ensure that any water flow is controlled in magnitude and flows into the cavity rather than outward, and that any chemicals are removed to the surface by borehole in gaseous form.

This issue was discussed in some detail by Blinderman and Fidler (2003), referring to two specific case histories in the USA (Hoe Creek and Carbon County) where benzene contamination of groundwater was documented. Benzene is accepted as a carcinogenic chemical and is of greatest concern in relation to potential contamination of groundwater systems. While other chemicals requiring monitoring also exist in the production gases (e.g. toluene, phenol), acceptable levels of these compounds are higher than benzene, although the same principles in evaluation, monitoring and control are applicable.

At the Hoe Creek tests (1976–1979), benzene levels in surrounding aquifers as high as 3000 parts per billion (ppb) were reported up to 100 m from the gasification cavities, reducing to 810 ppb in the mid-1990s, some 20 years after the tests were undertaken (Blinderman and Fidler, 2003). These levels resulted from

- an excessive and extended cavity pressure exceeding the groundwater pressure
- the shallow depth of the test (37 ft (11·3 m) of coal to a depth of 150 ft (45·7 m)), which led to roof caving breaking through to the surface (see Figure 2) and
- the presence of a significant aquifer system above and within the coal seam.

At the Carbon County trial (1995), where excess injection pressures were used for well connection, benzene levels in the target coal seam were reported to be in the range 5–10 ppb 3 years after test completion, although a reading of 49 000 ppb was reported in one monitoring bore.

Of these two examples of benzene impact, the Hoe Creek test is the one most often quoted as an example of the environmental harm that might occur with a UCG project because of the high levels and extent of the benzene observed. However, it is clear that the site selection work was grossly inadequate in relation to both the depth/thickness ratio applicable to the coal seam and the presence of local aquifer systems – factors that are well understood and incorporated into current UCG project site selection.

Blinderman and Fidler (2003) confirm that these are the only examples of benzene impacts out of more than 30 tests undertaken in the USA since the 1970s, which include the well-documented RM1 test programme at Hanna, Wyoming. As there is no confirmed evidence from recent test programmes of environmental harm from any chemical impact of the process on groundwater, it might be expected that this environmental issue should not be a retardant to commercialisation of the UCG process. Unfortunately, this has not proved to be the case.

The UCG process is quite complex, requiring detailed technical knowledge in a variety of disciplines and involving chemical processes occurring underground, which can only be understood and managed from the surface with the aid of a number of monitoring procedures. These complexities make presentation of the technology in the public domain quite difficult. The consequences of this position are discussed in more detail in later sections.

5.2 Australian case histories for benzene

At the Chinchilla site in Queensland, Blinderman and Fidler (2003) reported benzene levels of approximately 10 ppb in the

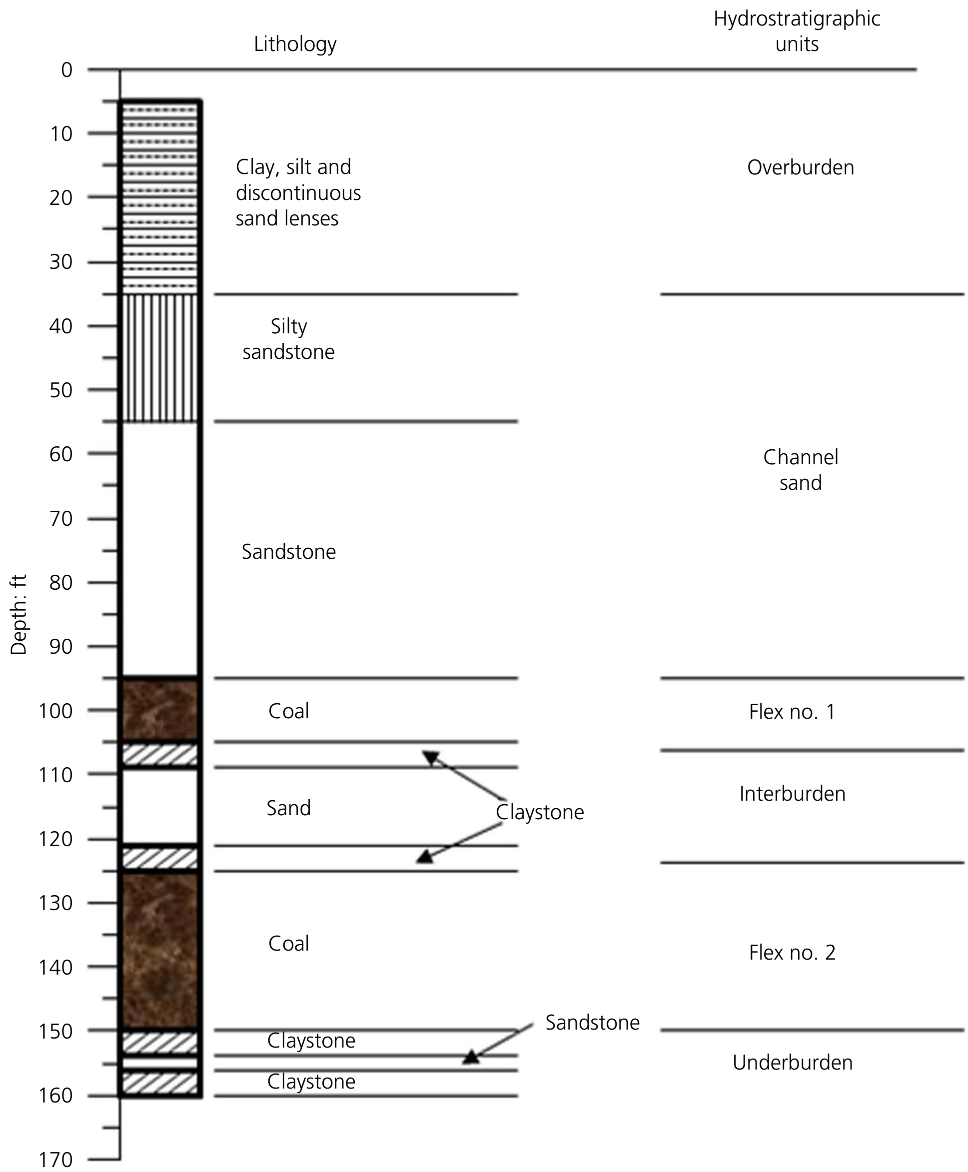

Figure 2. Hoe Creek UCG trial – profile summary (vertical scale in feet (1 foot = 30·5 cm)

coal seam within 50 m of the UCG gasifier area, and a similar reading was obtained approximately 200 m away as a result of the high directional permeability resulting from cleat structures in the coal seam. These data were obtained after completion of the controlled shut-down process in 2002, although no subsequent data were published to indicate potential longer term decay of this benzene level. However, the authors quote experience in the former Soviet Union (Dvornikova, 1994) showing that chemical concentrations in the coal seam 'tend to return to the baseline levels over 3 to 5 years after the end of gasification'. This evidence supports the option of controlled cavity rehabilitation over a period of time.

Because of its carcinogenic properties, irrational responses can be generated by the presence of benzene in the process and are well illustrated by the experience of Cougar Energy at its Kingaroy site in Queensland (Cougar Energy, 2011). Coal ignition occurred on 15 March 2010, but progress was impacted by a production well failure shortly after ignition, leading to a detailed investigation and subsequent installation of two new process wells. Two readings of benzene of 2 ppb were recorded in a 2-week period in May/June 2010, the data coming from one of a number of overburden wells located above the coal seam 250 m from the gasifier zone. Neither of these readings was obtained from an aquifer system from which drinking water was abstracted. Air injection was suspended on receipt of the first of the readings. Subsequent readings were at 1 ppb (the Australian Standard for drinking water and the limit of detection), then below the detection limit. The data were discussed with the relevant government authorities in late June 2010 and the company continued with its earlier planned re-ignition of the coal seam (Cougar Energy, 2010).

On 13 July 2010, Cougar Energy received and reported a reading of 84 ppb purported to come from an overburden monitoring bore from which no previous measurement of benzene had been recorded. In providing these data to the government authorities, the company advised of the likelihood that this was an erroneous reading, and supported this on 14 July 2010 with a further check result from the same bore that showed no benzene at the level of detection (Cougar Energy, 2011). Despite also receiving a letter dated 16 July 2010 from the testing laboratory confirming that the reading was the result of a mix-up of samples and that the correct sample recorded no benzene, and their own sample test results confirming this conclusion, the relevant government department on 17 July 2010 (Cougar Energy, 2011) issued a shut-down notice on the site. Evidence (Cougar Energy, 2011) suggests that this was a result of pressure from a number of local residents expressed through their local member of parliament. No subsequent readings of benzene above the detection limit were recorded at the site, despite widespread monitoring over the following years. However, the shut-down order was confirmed and is still enforced.

Following these events, the government, through its use of an advisory panel set up in October 2009, has delayed any approval for UCG to be developed in the state (DEHP, 2013) – an issue discussed further in section 6.

In the author's opinion, this experience confirms the need for both UCG developers and governments to finalise, in advance of any site activity, a rigorous and precise methodology to define all relevant contaminant trigger levels, and the required reporting and response actions, to serve as an integral part of the environmental approvals and compliance process, and to give project development certainty to the investor.

5.3 Considerations in regulating benzene levels

The starting point for assessing the significance of acceptable benzene levels is the classification/zoning of any overlying water resource or aquifer. Where the water resource is used for human consumption, reference should be made to the level acceptable for drinking water. This level is measured in micrograms/litre or parts per billion. Different countries have different standards required for drinking water, with the World Health Organization (WHO) adopting a figure of 10 ppb. This standard is based on an assessment that a human, drinking 2 l of water per day for 70 years will have a 1 in 100 000 extra chance of developing cancer (WHO, 2011). As with all standards, it is important to recognise the actual limits and capabilities of measurement services available in specific countries to detect the stated value.

Assessing an acceptable level for benzene in a coal seam that is actively involved in the UCG process but is not classified as a water abstraction aquifer is a more difficult exercise. The reference commonly used is the guidelines for fresh and marine water quality (Australian Government, 2000). Under these guidelines, recommended trigger levels for benzene at the 95% level of species protection are 950 ppb (freshwater) and 700 ppb (marine water).

With acceptable levels of benzene in groundwater potentially varying from 10 ppb to 950 ppb, it is evident that each specific UCG location requires individual consideration in the selection of a relevant benzene trigger level. Factors of relevance include the following.

- Whether the water is in the coal seam or overburden. If in the coal seam, natural decay of levels of benzene with time after completion of operations is likely.
- Whether the water is being used for drinking, or is likely to be used for drinking, in the period of process operations.
- The regional groundwater hydrological system. If contaminants do escape, data are required to show where they will be carried and how rapidly, and whether dilution will occur.
- If contaminants are observed, how will they be treated and over what time period?
- What is the level of any observed contaminant in relation to the approved trigger level?

In order to quantify these factors, a comprehensive groundwater monitoring programme is essential to provide relevant information on water quality before, during and after completion of UCG operations. Historical evidence gives comfort that application of sound site selection procedures and careful process control will ensure that failure of the type evident at Hoe Creek will not occur. In addition, the installed monitoring system, combined with a reporting and action response plan, will give the regulatory authorities the mechanism to enforce the agreed environmental management plan, and should form the basis for an open and transparent integration of all stakeholders in the compliance reporting process.

As UCG is likely to generate chemicals such as benzene in a controlled pressure environment of high temperature, and the relevant chemical reactions will create impacts in a zone in the immediate vicinity of the cavity, it is essential that trigger levels for any potential contaminant apply outside a defined 'barrier zone' around the cavity (say 200 m), with rehabilitation of this zone being required after the operation is complete. This is no different in principle from the requirement for conventional mining operations to utilise a similar 'barrier zone' within which (for example) containment of contaminated runoff water may be required.

6. Political issues

At the time of writing, the commercial development of UCG is caught up in an international political climate involving the debate about pressurised water fracking

- in shale gas recovery with the addition of chemicals
- in coal seam gas (CSG) recovery with or without chemicals and
- in UCG operations, used occasionally but never with chemicals.

Much of the debate on these issues is undertaken without technical discussion, as the technologies are complex, often confused and seldom differentiated – a measure of the difficulty in having technical concepts conveyed in a simple manner to the public. Even with no fracking, the UCG process will generate chemicals in the vicinity of the gasification chamber and must therefore address the issue of potential groundwater contamination, despite evidence that distortion or misunderstanding of technical data may be expected.

The impact of political issues on the development of UCG technology is well illustrated by developments and decision making in Queensland over the past decade. The successful Chinchilla burn started in 1999, and by 2007 three commercial UCG projects were being promoted in that state, with pilot phase burns initiated at all sites. Yet the future of the technology in Queensland is now uncertain, despite no evidence of threat to the environment. The shut-down of the Kingaroy UCG project by the Queensland government discussed in section 5.2 reinforces the need for clarity in defining the environmental criteria within which the UCG process can be operated prior to project initiation, to minimise the prospect of political issues referred to above coming into play.

Over the past 10 years, the Queensland government has given strong support to an expanding CSG industry (DNRM, 2014), leading to conflicts of overlapping tenure between the Petroleum and Gas (P&G) Act (for CSG) and the Mineral Resources Act (for UCG) legislation. The Mineral Resources Act (1989) defines coal used for the UCG process as a 'mineral f' (section 6 (2) (f)) and further specifies that in relation to granting a mining licence for a 'mineral f', the minister may decide any issue involving conflict of overlapping tenure on the basis of 'public interest' – a difficult concept to define.

In relation to this issue, in February 2009, the Queensland government released a UCG policy paper (Mines Industry, 2009), which stated that

> the Minister for Natural Resources, Mines and Energy, if asked to determine a coordination or preference decision between the developer of a CSG resource and the developer of a UCG resource, the decision will be made in favour of the CSG tenure holder under the P&G Act, so as to allow the CSG tenure to progress to production stage.

This declared preference, taken together with the government's actions in relation to the existing pilot burns, has effectively precluded any further development of the UCG industry in that state for many years.

It is worth recording that the past massive development of UCG technology in the former Soviet Union and the modest development work undertaken in the USA both occurred as a result of government funding and ceased with the withdrawal of government financial support. Over the past 15 years, there has instead been a significant financial investment from non-government sources pressing for commercial UCG development, which is now restrained in Australia by government environmental regulation.

7. Conclusion

From a situation in recent years when UCG gas was being produced from three plants in Australia, one in South Africa and one in New Zealand, the South African project currently appears to be the only one with a prospect for development over the next 5 years. This is despite the fact that there seem to be few resource and technology barriers to commercial UCG development and a clearly demonstrated need, particularly in the Asian region, for alternative clean energy sources using the vast available stranded coal resources.

This analysis of factors relevant to achieving the goal of successful commercial development clearly points to a complex environmental/political interaction as the main constraint to progress of the technology, as illustrated by the Australian experience. This is despite its many environmental and economically attractive features that appear to be well accepted and the lack of factual evidence from the last 15 years of UCG field work to suggest there is any realistic threat of environmental harm from use of the process.

The constraints to development have come from the pressure of environmental and competing commercial lobby groups with significant influence in the local economy, their relatively large resource base compared with the embryonic UCG lobbying capability, and the impact of the technical complexities associated with the UCG process.

The challenge then for the UCG industry is to find markets (countries or local communities) where there is a strong demand for the benefits that UCG technology will bring, supported by local authorities and industry agreeing on the controlled environmental management of the process. In addition, and in order to minimise financial risk, there are significant benefits in defining initial power projects that are commercially viable at a small scale (say 20–30 MW). Such an approach is currently considered as being relevant for Indonesia (https://ascotenergy.com.au/) and is likely to be applicable to other developing countries.

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