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Towards commercialising Underground Coal Gasification in EU

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Abstract

Modern "enabling technologies" and over a century of research and development have pushed underground coal gasification (UCG) beyond the proof-of-concept phase. Lessons learned from previous trials have demonstrated that UCG can exploit energy stored in coal efficiently and with limited environmental impact compared with conventional coal-based energy technologies. Many countries in the EU (and world-wide) struggle to meet their energy needs despite containing very large reserves of coal, which cannot be exploited conventionally because of its depth. Application of modern UCG techniques, state-of-the-art drilling and monitoring technologies offer the opportunity to extract the energy from deep coal resources economically and with limited environmental impacts; however, several hurdles, such as public opinion and CO_2 emission limits, must be overcome before UCG can commercialise in the EU. The EU has a long history of supporting UCG projects and has funded some of the most important research undertaken to date. Continued support by member states will attract more private investment, enable more field trials and allow Europe's world-class UCG experts to demonstrate that the technology is ready to provide cleaner energy from coal for the EU in the 21st Century. This is a review paper which aims to summarise the lessons learned from UCG trials and EU-sponsored work, and to discuss what still needs to be done to commercialise UCG.

Keywords
Clean Coal Technology; Energy; Underground Coal Gasification

1. Introduction

Despite the current drive to reduce pollutant and carbon dioxide emissions from fossil fuels, coal and other fossil fuels will continue to be a major source of energy in the future. According to the International Energy Agency (IEA 2014), the global demand for coal will increase on average by 2.1% per year through 2019, being mainly driven by emerging economies. Despite the increasing contribution of renewable energy sources, it is difficult to see how targets for emissions reduction from fossil fuels can be achieved using current conventional coal-based technologies. The key to balance the tension between increasing coal use and the requirements for reduced pollutant (e.g., particulates, NOx and SOx) and CO_2 emissions is the use of clean coal technologies (CCT). One such technology is Underground Coal Gasification (UCG), which has the potential to contribute to the future energy needs of coal-bearing countries in the EU (and world-wide) in a cleaner and safer way (Stanczyk et al. 2011; Sheng et al. 2014; Creedy et al. 2001; Friedmann et al. 2009; Bhutto et al. 2013).

UCG is the same chemical process used commercially by surface gasification plants to convert solid coal into a mixture of mostly combustible gases (e.g., CH_4, CO and H_2) known as synthesis gas or “syngas.” Unlike surface gasification, UCG is undertaken in-situ in deep, carefully-selected coal seams that are otherwise unminable (Fig. 1). The coal is gasified by injecting oxidants through a borehole (the injection well) into the coal seam and partially combusting the coal. The syngas flows at very low velocity and under pressure to a second borehole (the production well) and to the surface, leaving almost all of the coal-ash behind. The combination of linked injection and production wells is known as a “module.” Once at the surface, conventional technologies are used to remove the remaining pollutants and to generate electricity or manufacture liquid fuels and industrial chemicals from the syngas.

Compared with conventional coal-based energy technologies, UCG has a significantly lower environmental impact because coal is not mined, transported or processed and because it generates significantly smaller volumes of waste products (e.g., fly-ash) and pollutants. Coupled with existing technologies for carbon capture, UCG has the potential to recover energy from coal with reduced CO_2 (Roddy & Younger 2010; Kempka et al. 2011; Sarhosis et al. 2013).

Despite its potential, and over a century of development, UCG has never been commercialised. Now, however, the results of several field trials and new enabling technologies (e.g., directional drilling) have pushed UCG beyond the “proof-of-concept” phase and into the commercialisation phase. This is a review paper which aims to summarise the lessons learned from UCG trials and EU-sponsored work, and to discuss what still needs to be done to commercialise UCG.

2. Demand for UCG in the EU

Many EU member states are heavily reliant on a single supplier of primary energy, including six who are entirely dependent on natural gas imports. In response to the winter gas shortages in

2006 and 2009, and recent geopolitical issues, the need for diversified, resilient, low-carbon domestic energy sources is of extreme importance for Europe. Efforts to develop renewable resources have met considerable success, but fossil fuel usage is expected to account for up to 66% of primary energy consumption until at least 2035 (BP 2015).

At the same time as indigenous energy supplies become ever more important, the EU's fossil fuel resources, particularly oil and gas, are declining and gas imports are set to increase significantly (BP 2015). Europe's coal resources remain large, but underground coal mining becomes more difficult, dangerous and expensive as the shallow, easily-mined coal is progressively consumed; mining below 500 m is generally not economic, yet 80% of Europe's coal resources lie below this depth (EuraCoal 2013). These resources could be recovered economically by UCG, which is uniquely suited to exploiting deep unminable coal with reduced environmental impacts compared with conventional technologies.

Data on coal resources suitable for UCG in Europe are limited, but a conservative estimate by the British Geological Survey indicates that the UK alone has about 16.7 Bt of coal suitable for UCG, which, according to UCGP (2007), equates to about 1,700 Bcm natural gas or 17 years of extra gas reserves. For similar coal-rich/gas-poor countries, such as Poland and other eastern European countries, UCG could offer an important opportunity to become less reliant on gas imports.

3. Lessons learned on the path to commercialisation

There have been a total of around 50 UCG trials undertaken in the former USSR, USA, Canada, Europe, China, South Africa, New-Zealand and Australia. Despite most of the trials being short-lived, except for the Yerostigaz project in Angren, Uzebekistan (which has been operating for over 50 years), more than 15 Mt of coal have been gasified in-situ (Younger, 2011). The trials showed that UCG is highly adaptive to different conditions; it has been undertaken in horizontal seams and steeply dipping seams (i.e., coal seams that have been re-orientated from horizontal to angles over 60 degrees), as well as in coals of different rank and at different depths, from <50 m to 1,500 m deep.

The trials also demonstrated that UCG is a highly efficient coal conversion process, with gasification efficiencies (i.e., the ratio of the energy in the coal gasified to that in the produced syngas) of 75–85%, which is similar to that of surface gasifiers (Cena et al., 1988), and mining efficiencies (i.e. the ratio of the mass of coal removed by gasification to the mass of coal originally in place) at around 60%, which is comparable to underground coal mining. Although not all of the trials were successful, and some early trials unfortunately caused environmental damage (e.g., the US "Hoe Creek" trials in 1970s), they have provided the lessons necessary to move UCG beyond the proof-of-concept phase. The key lessons are:

a) Choose the most efficient UCG module design;

b) Operate and monitor the facility according to strict guidelines;

c) Manage geoenvironmental risks;

d) Choose the correct site; and

e) Commercialise progressively.

3.1 UCG modules

All UCG modules require a minimum of an injection well to inject the oxidising agents and start ignition and a production well to recover the syngas. There are currently three types of module configuration: the Linked Vertical Well (LVW); the Controlled Retracting Injection Point (CRIP); and the Steeply Dipping Bed (SDB) (ref. Fig. 2).

LVW is the oldest of the three configurations and was developed during a major phase of experimentation in the former USSR. Variants of the LVW method are still used today, most notably at the Angren, facility in Uzbekistan. The LVWs can be linked by enhancing the natural permeability of the coal seam, by using techniques such as 'reverse-combustion' (Blindermann et al 2008), electro-linking or hydro-fracking (Couch 2009), or by using a third directionally-drilled borehole to link the wells. The latter technique was first tested during a US trial known as Rocky Mountain 1 and is thought to have been used in the early phases of some Chinese, Australian and South African projects.

The CRIP method was first used in the 1980s by the USA and was developed further during trials in Spain (1990s), Australia (late 1990s to present) and recently in Alberta, Canada. Two different CRIP configurations have been developed; the linear CRIP (L-CRIP) and the Parallel CRIP (P-CRIP). In the L-CRIP configuration, the injection well is drilled along the base of the coal seam to intersect the production well and gasification proceeds along the in-seam section of the injection well. This technique was most recently used at the 1,500 m-deep UCG trial at Swan Hills, Alberta, Canada (Swanhills Synfuels 2011).

In the P-CRIP configuration, both process wells are drilled parallel to each other within the coal seam. Once the in-seam sections have reached a pre-determined length the two process wells are deviated towards the base of a third borehole drilled vertically into the coal seam. The third well is used to ignite the coal at the start of operations. This technique was first tested during the "Tono 1" trial in US and again in the Rocky Mountain 1 trial, where it was compared directly with a LVW module (Cena et al., 1988).

The SDB configuration was used for gasifying coal in steeply dipping beds during early trials in Russia and Europe, and was developed further in the USA at trials in Rawlins, Wyoming during the 1980s, with some considerable success (Burton et al., 2006; Couch, 2009).

Whilst LVW modules are relatively inexpensive to build (the directional drilling required by CRIP modules is expensive), there are several reasons why this technology is falling out of favour. Previous trials, particularly the RM-1 trial, have shown that CRIP modules gasify coal more efficiently than LVWs (Cena et al., 1988) and that LVW suffer from the "overriding effect," where gasification occurs progressively higher in the coal seam until it occurs only across the top, leaving the coal beneath unaffected. Furthermore, LVW modules depend on enhancing natural permeability to link the wells, but as natural permeability decreases with increasing depth, there becomes a point at which it is not possible to complete the link between process points. These factors, together with the current trend towards deeper gasification (Younger, 2011) have resulted in CRIP configurations being increasingly favoured in recent attempts to commercialise UCG.

3.2 Operating and monitoring UCG reactors

The correct operation of UCG modules is essential for protecting the environment and ensuring efficient gasification. Three factors are critical: 1) the pressure of the reactor compared to that of the surroundings; 2) gasification efficiency; and 3) reactor decommissioning.

Operating and monitoring UCG reactors

When operated properly, the pressure of a UCG reactor depends on the rate of oxidant and water injection, and the rate at which the syngas can exit the production well. If the pressure becomes too high, however, a third factor becomes important; gas loss via leakage through the reactor walls. To avoid this, UCG should take place in low permeability coal and rocks that are water-saturated. Water in the pore spaces of the rock seals the reactor and ensures it remains a "closed system." The closed system will only be maintained if the reactor pressure is less than the pore-water/groundwater pressure (or hydrostatic pressure). If the reactor pressure exceeds the hydrostatic pressure, syngas will be forced through the pore spaces in the rock/coal surrounding the reactor, displacing the pore-water and escaping into the surroundings (Fig. 3). UCG operators now continuously monitor reactor pressures to ensure that they never exceed hydrostatic pressure.

Gasification efficiency

During UCG, gasification and pyrolysis occur simultaneously. Gasification occurs at higher temperatures and produces low-molecular-weight gases that are removed efficiently from the UCG reactor. In contrast, pyrolysis occurs at lower temperatures and produces high-molecular-weight compounds, some of which readily condense in the subsurface, are potentially-contaminative and are difficult to remove from the system. It is therefore necessary to maximise gasification over pyrolysis by minimising the amount of heat lost from the system i.e. maximising the gasification efficiency. This is achieved by using the most efficient UCG module configuration and by choosing the most efficient oxidant and oxidant injection rate (Cena et al. 1988; Osborne 2013; Konstantinou and Marsh 2015). As is generally the case for surface gasification, pure oxygen is used instead of air (or enriched-air) in modern UCG because it improves gasification efficiency (>20% increase) and reduces the volumes of gases flowing through the module, which lowers the cost of building UCG modules because smaller diameter boreholes and completion equipment are required. Use of pure oxygen also increases the calorific value of the syngas from lower than 4 MJ/Nm^3 with air to >12 MJ/Nm^3 with pure oxygen.

Decommissioning

UCG operators have to carefully decommission UCG modules after use because the reactors can remain very hot for time periods in the order of years (Sarhosis et al. 2013). Left unmanaged, high reactor temperatures can allow coal to continue to pyrolyse and water to vaporise, which could raise the reactor pressure above hydrostatic pressure and elevate the risk of environmental impact. To prevent this, the “clean cavern” technique was developed (Boysen et al., 1990), which involves quenching the reactor with water and nitrogen to quickly stop coal pyrolysis. The reactor is allowed to vent continuously during quenching to avoid the pressure exceeding hydrostatic pressure. The water recovered at the surface is processed to recover pyrolysis products.

3.3 Manage Geoenvironmental Risks

Some previous trials, particularly the US “Hoe Creek” trials undertaken in the 1970s, caused groundwater contamination and subsidence. Although the ground used by the Hoe Creek trials has since been remediated, the unfortunate incidents have enabled the environmental risks of UCG to be understood and risk-management strategies to be developed.

Disregarding the reactor pressure (for discussion, see above), the risks of pollutant migration out of the georeactor and of surface subsidence are associated closely with the development of the subsurface cavity (i.e., the georeactor). As coal is progressively gasified, the overlying strata becomes unsupported (in essentially the same way as with coal mining, although the surrounding strata remain water-saturated during UCG), causing loss of support to the overburden and a build up of stress. The exact geomechanical response of overburden to the development of a UCG cavity is highly complex and strongly influenced by site-specific conditions (e.g., the thickness and strength of overlying rock layers, dip angles and the existence of faults etc). Nevertheless, Younger (2010) discusses generic geomechanical responses to UCG that could be expected above a UCG reactor in horizontal strata: Initially, the UCG reactor will collapse and be filled by brecciated roof rocks (or ‘goaf’). Above the breccia-filled cavity, an inverted cone-shaped zone of deformation develops that is defined by an “angle of draw” (Fig 4). Rocks immediately above the cavity (extending for about one third the width of the UCG cavity) undergo extensional deformation and crack and sag as a result. Above this initial extensional zone, rock layers become compressed, in a “pressure arch”, above which a second zone of net extension extends towards the surface. Rock permeability within the zones of net extension become enhanced, and those in the "pressure arch" become diminished, and can act to further isolate any overlying aquifers from the georeactor. This simplified picture, however, is complicated if pre-existing fault surfaces exist within the zone of deformation.

As it is not feasible to build structures to support the overburden during UCG, risk management strategies are focussed on choosing a site with the appropriate geology. The key is to minimise the development of preferential pathways to sensitive 'receptors' (i.e., shallow potable aquifers and the surface) by choosing deep coal seams (i.e., > 300 m deep) that are overlain by thick, strong, low permeability layers (such as silt stones and mudstones) with minimal fractures.

The deeper the coal seam, the less the probability of surface subsidence (Yang et al. 2014 and Mastalerz et al., 2011) and a minimum of 15 m of consolidated rock above the coal seam is recommended (Mastalerz et al., 2011). The closer UCG is undertaken to a fault, the higher the risk of fault reactivation and gas leakage (Creedy and Garner, 2004; Sury et al., 2004; Burton et al., 2006), and, according to Williams (1998), a minimum distance of 0.8 km from major fault zones should be adopted. The acceptable distance between a UCG site and a fault zone, however, should be determined on a site-by-site basis (Sheng et al., 2015).

Relatively impermeable rock around the coal seam helps to prevent the escape of product gases, as well as reducing the flow of ground water into the seam. Gases and pyrolysis contaminants in and around the gasification cavity should be 'contained' by groundwater if pressures within the gasification reactor are less than or equal to hydrostatic pressure.

In order to further control the subsidence of a commercial UCG development, coal pillars are left between two adjacent L-CRIP modules, as is the case for coal mining. The width of the pillar compared to the maximum cavity width is determined prior to designing the UCG drilling panel and be based on the geomechanical properties of the overburden.

3.4 Site Selection

One of the most important elements of risk management is site selection (Mastalerz 2011; Sheng et al. 2015). Although a number of quantitative and semi-quantitative site selection criteria have been published (e.g., Oliva and Dena 1991; Mastalerz et al., 2011), it is now generally accepted that UCG should take place in deep coal seams (typically > 300 m) and overlain by rock with high mechanical strength, low permeability and minimal faulting (Sheng et al., 2015). The target coal seam and surrounding rocks should be saturated with water and not be located near any groundwater resources (DECC 2014).

In addition to minimising environmental risks, site selection plays a key role in ensuring that a commercial UCG project is profitable (Nakaten et al., 2014a). Ignoring the effects of gasification efficiency and coal quality, the greater the volume of coal converted per module, the more economic the project is. The volume of coal converted per module depends on the coal seam thickness, the inseam length (i.e., the distance between injection and production wells) and the volume of the in-situ reactor. Whilst coal seam thickness is clearly an intrinsic property of a coal seam that cannot be changed, the other two factors are limited by site conditions and must be optimised in order to maximise the project's profitability (Nakaten et al., 2014b).

Coal quality (i.e., the energy density of the coal) also plays a fundamental role in ensuring a profitable UCG project. The higher the calorific value of a coal, the more energy can be recovered per module and the better the project's economics (Nakaten et al., 2014b).

Depending on the depth of UCG (i.e., from 300–1500 m deep), fully-optimised UCG modules could be expected to produce raw syngas at a rate equivalent to 30 – 150 $MW_{thermal}$. Such power outputs are probably too small to support a commercial UCG project and so multiple modules will have to be operated simultaneously. The UCG industry has limited experience of operating multiple UCG modules simultaneously and it is recognised that future commercial projects would require time to demonstrate to investors, regulators and the general public that economic and financial risks from the technology can be managed. Operating in the natural environment is one of the key aspects that has to be worked on. It will therefore be necessary to grow projects progressively, from the initial one or two modules (*"early-commercial")* to perhaps six to seven (*"semi-commercial"*) to ten or more modules (*"full-commercial"*) operating simultaneously. Eventually, this will be able to provide confidence and long-term commercial guarantees for the environmental impact, gas quality and specification. The UCG industry could potentially take a similar path to full resource development took place in the CBM industry in the USA (Climate Change 2001); with the aid to full commercial development in many coal producing countries in Europe and along the globe.

4. Enabling technologies

Technical advancements in directional drilling, seismic surveying, high temperature- and acid gas-resistant well engineering, and in situ controlling and monitoring techniques have been key in pushing UCG beyond the proof-of-concept phase. Directional drilling is a technique that allows boreholes to be drilled at various angles, with trajectories controlled such that a borehole can be made to intersect another over a kilometre away. Modern drilling technologies (e.g., measurement-while-drilling and down-hole motor technologies) have been used by the oil and gas industry for decades and have more recently allowed the coal bed methane and shale gas industries to commercialise. The now routine use of directional drilling in these industries has greatly reduced its cost, making it an affordable "off the peg" technology for UCG.

Recent developments in seismic source generation (e.g., seismic vibration technology and improvements in seismic processing from the oil and gas industry) have now made it possible to produce accurate, high resolution maps of coal seams to depths of around 2 km. Knowing how the coal seam changes improves the accuracy of directional drilling by allowing the driller to anticipate changes and maintain the borehole in the correct position at the base of the coal seam.

Previous trials demonstrated that the chemical and physical conditions encountered during UCG could be detrimental to the conventional borehole completion materials used by the oil and gas industry. Advancements in borehole material manufacture (e.g., stainless, nickel and duplex-steel alloys) have made it possible to construct UCG modules from modern corrosion-resistant materials and precision-manufactured components, improving their longevity and integrity under the challenging conditions of UCG.

Careful, real-time controlling and monitoring of UCG is essential to maximise efficiency whilst minimising environmental risks. Until relatively recently, there were few options available to control and monitor the conditions in real time. New down-hole controlling and monitoring technologies, such as Optical Time Domain Reflectometry and Distributed Temperature Measurement via fibre optic cables, developed by the oil and gas industry allow direct measurement UCG reactor conditions, enabling the operator to carefully control UCG in real time. Other technologies allow the UCG reactor to be monitored from the surface, such as micro-gravimetric and micro-seismic methods, while gas tracer tests and mass balance calculations allow the volume of the reactor to be predicted, as well as the detection of gas leakage.

5. Summary of UCG activities in EU

5.1 Previous trails

Europe has a long history in undertaking UCG trials, beginning with the trials at Bois-la-Dame, Belgium in 1948, the trials at Newman Spinney, UK (1949–1959) to the trials in Polish coal mines in 2014. These trials were undertaken at shallow depth (<100 m); the most significant trials for the commercialisation of UCG were undertaken at greater depths. The first of these was the EU-funded Belgo-German UCG experiment in Thulin, Belgium during the late 1980s, which was the first to be undertaken at over 800 m. The Thulin project initially used LVW techniques and demonstrated that more advanced techniques (i.e., directional drilling) were required to gasify deep, low permeability coals. The project subsequently used short-radius directional drilling and well completion materials adopted from the oil and gas industry to create the first ever deep L-CRIP module.

The second major phase of development was an EU-funded trial between Spain, Belgium and UK during 1991–1997. The UCG trial at El Tremedal, Teruel Province, Spain demonstrated the technical feasibility of carrying out underground coal gasification at a depth of 600 m using the L-CRIP technology. The effectiveness of L-CRIP at gasifying deep coal has since been further validated by a trial at 1,400 m depth in Alberta, Canada.

5.2 Summary of current EU-funded research

Following the UCG trials, the EU-based Research Fund for Coal and Steel (RFCS) has provided significant funding to support further research in the UCG. The first of these were the Hydrogen Oriented Underground Coal Gasification for Europe projects (HUGE, 2007–2010 and HUGE2, 2011–2014), which were coordinated by the Central Mining Institute in Poland (Yulan et al. 2007). The second was known as UCG & CO_2 Storage project (2010–2012) and currently the COAL2GAS project (2014-2017) is investigating UCG in Romania. Several EU-based universities currently carry out research into UCG modelling (e.g., Yang et al., 2014) and CO_2 storage (e.g., Sarhosis et al., 2013; Sheng et al., 2014) and undertake laboratory-based experiments (e.g., Stanczyk et al. 2011; Kempka et al. 2011; Kostantinou & Marsh 2015). Collaboration and sharing between these and other projects has been key to the development and growth of the UCG industry.

6. Commercialising UCG: Overcoming barriers at the European level

6.1 Regulatory hurdles and political issues

Although UCG is ready for commercialisation, the technology remains new to the general public and to regulators. Licensing policies are present in some countries (e.g., Australia, UK, Canada, New Zealand, the USA), but the general lack of specific regulations, or knowledge of how to apply existing regulation, has restricted field trials and commercial development in many EU countries.

Government support of UCG field trials is needed to grow our knowledge base, gain more environmental data and to attract more private investment. Although it is recognised that investors have confidence in the long-term future of the UCG as an option for low carbon electricity production (e.g., Walker 2014; Nakaten et al. 2014a) the technology needs to "de-risked" from both economic and environmental perspectives in the near–medium term. This can be achieved by permitting field trials using modern approaches and state-of-the-art equipment, carefully monitored and regulated, to demonstrate that UCG can exploit the energy in coal resources with limited environmental impact compared with conventional technologies. Additionally, some commercial field projects could serve as to test the possibility of storing CO_2 in the spent reactors (and overburden) and evaluate other technologies, such as microbial production of methane from coal and/or methane production from the overburden.

6.2 Public perception

Before a field trial can be undertaken, it will be essential to gain approval from the local population as well as regulators and the local government; a key obstacle to UCG commercialisation is adverse public perception. Understanding public attitudes and the ways in which energy and technologies are themselves understood and used is vital for a technology to progress to commercialisation (e.g., Whitmarsh et al., 2011). A study carried out by Shackley et al. (2006) indicated that an open, transparent and consultative process of decision-making and operation should be adopted by the developer, operator and regulator. Also, the trial should be cited carefully, preferably in land with a history of industry (e.g., coal mining) and it should be made clear that UCG will never be undertaken in populated areas or environmentally-sensitive areas.

6.3 Reducing GHG emissions

UCG, like all fossil fuel-based energy technologies, produces CO_2. Carbon dioxide emissions will remain an important factor for UCG in the 21st century as the EU continues to reduce greenhouse emissions; UCG projects will have to limit CO_2 emissions to gain approval and not incur large financial penalties. The UCG industry is currently adapting to this by investigating the potential for combined UCG, and Carbon Capture and Sequestration/Utilisation (CCS/U), as well as re-use of CO_2 via processes such as enhanced oil recovery.

As UCG syngas is similar to other gases produced by industries, the technologies for capturing CO_2 from UCG syngas are in existence, well understood and widely available. Relatively little adaption of these technologies to UCG syngas will be required. The principal barrier to combined UCG–CCS is sequestration. Efforts continue around the EU to develop sequestration sites, but the progress is slow and this, above all others, is probably the most difficult obstacle to overcome for UCG to commercialise in the EU.

Although not a “magic bullet,” UCG does offer some advantages compared with conventional technologies regarding CCS. UCG produces syngas relatively inexpensively and is undertaken close to potential sequestration sites (such as deep saline aquifers or depleted gas reservoirs), limiting the cost impact of capture and sequestration. It may also be possible to inject carbon dioxide into the spent UCG reactors, but this is currently hypothetical and has never been tested. As with other fossil-fuel technologies, the future of UCG is intimately associated with the commercial development of CCS/U.

7. Conclusions

Although the idea of UCG dates back about 100 years, it has never been fully commercialised. Lessons learned from previous trials, together with advancements in key enabling technologies, have recently pushed UCG beyond the proof-of-concept phase, readying UCG for full commercialisation. Application of modern UCG techniques, state-of-the-art drilling, completion and monitoring technologies offer the opportunity to extract the energy from deep coal resources economically and with limited environmental impact. This combined with factors such as energy security has recently caused renewed interest in UCG in the EU, particularly in those countries with large but unminable coal resources and limited oil & gas reserves.

There are several hurdles, such as public perception and regulatory issues, which must be overcome before UCG can commercialise. The most significant hurdle is to reduce CO_2 emissions; a common factor to all fossil fuel-based energy technologies. Although not a "magic bullet," UCG offers several advantages over conventional coal technologies as it does not require mining or coal processing and transportation, but progress in CCS must be made before UCG can realise its full potential in the EU.

> The EU has a long history of supporting UCG research and has funded some of the most significant UCG trials undertaken to date. Collaboration and sharing expertise and knowledge between projects and governments with experience in UCG has been key to the development of the UCG industry. Continued support by member states is required to attract private investment, enable more field trials and allow Eur*ope's* world-class experts to demonstrate that UCG is ready to provide clean energy for the EU in the 21st Century.

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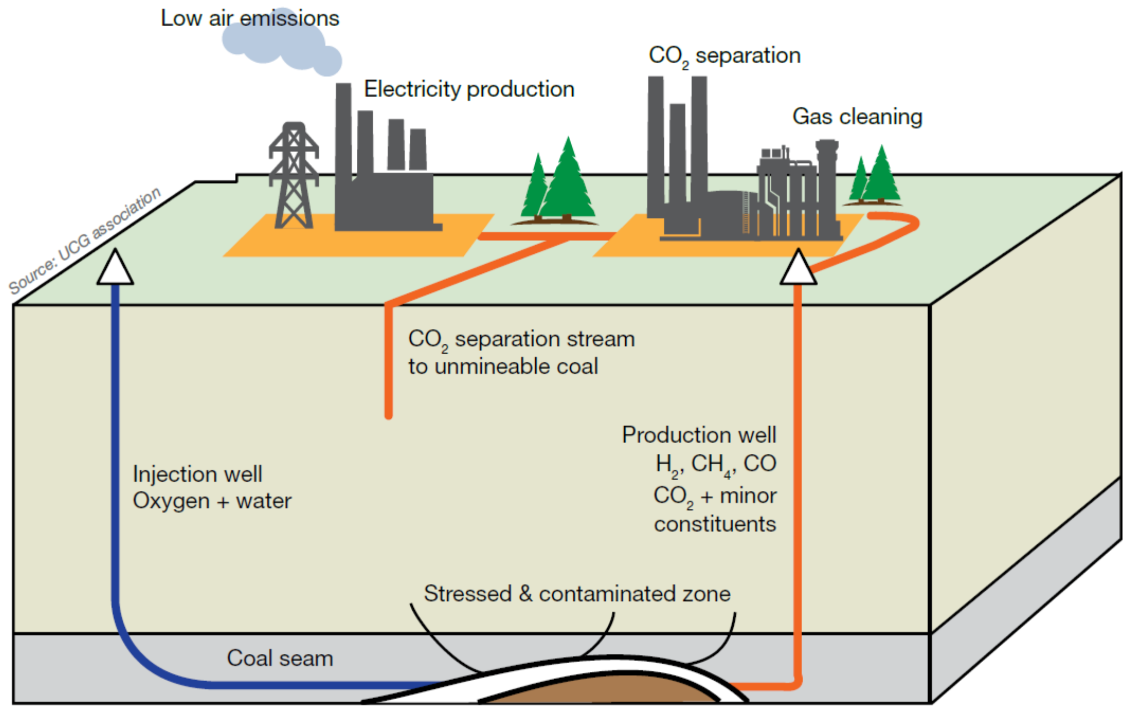
List of Figure Captions

Figure 1. A UCG module and possible surface plant (courtesy of the UCG Association - not to scale).

Figure 2. Module configurations for underground coal gasification development

Figure 3. Potential pathways for pollutant migration

Figure 4. Strata relaxation and fracture of rocks above the georeactor (Younger 2011).



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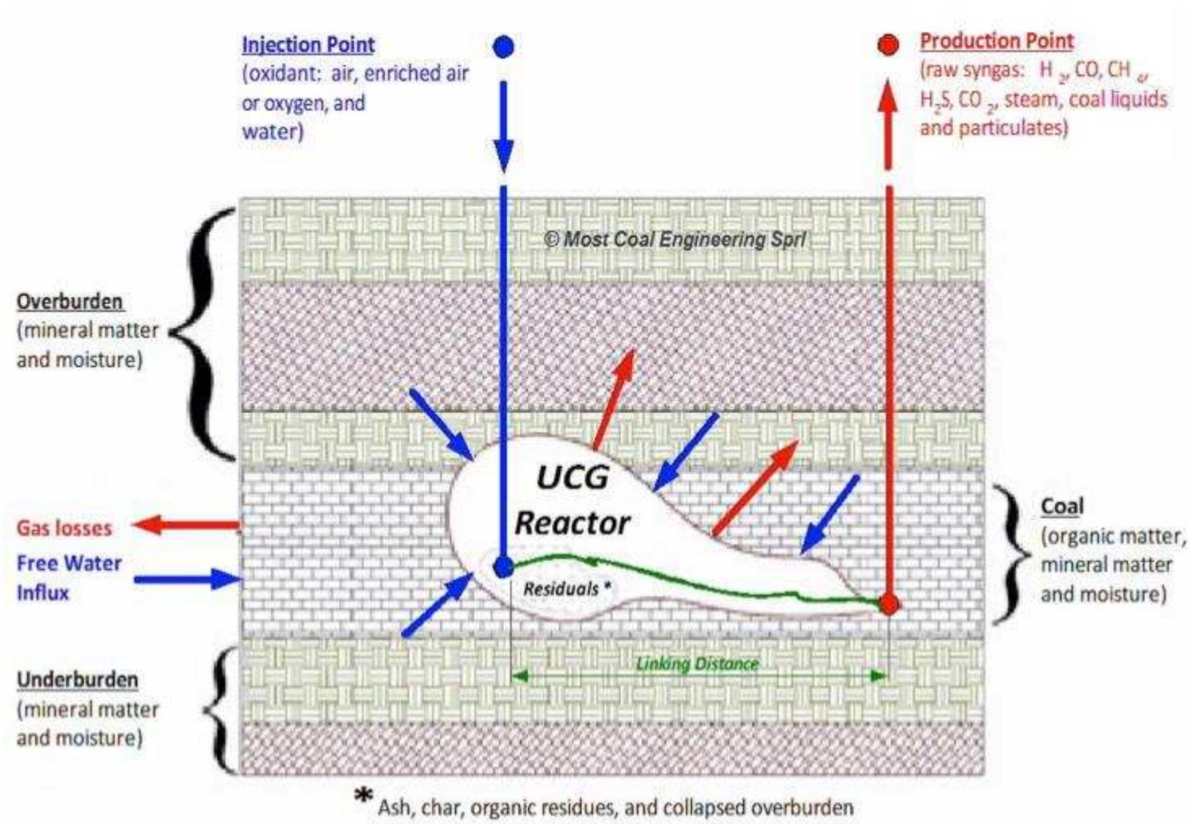
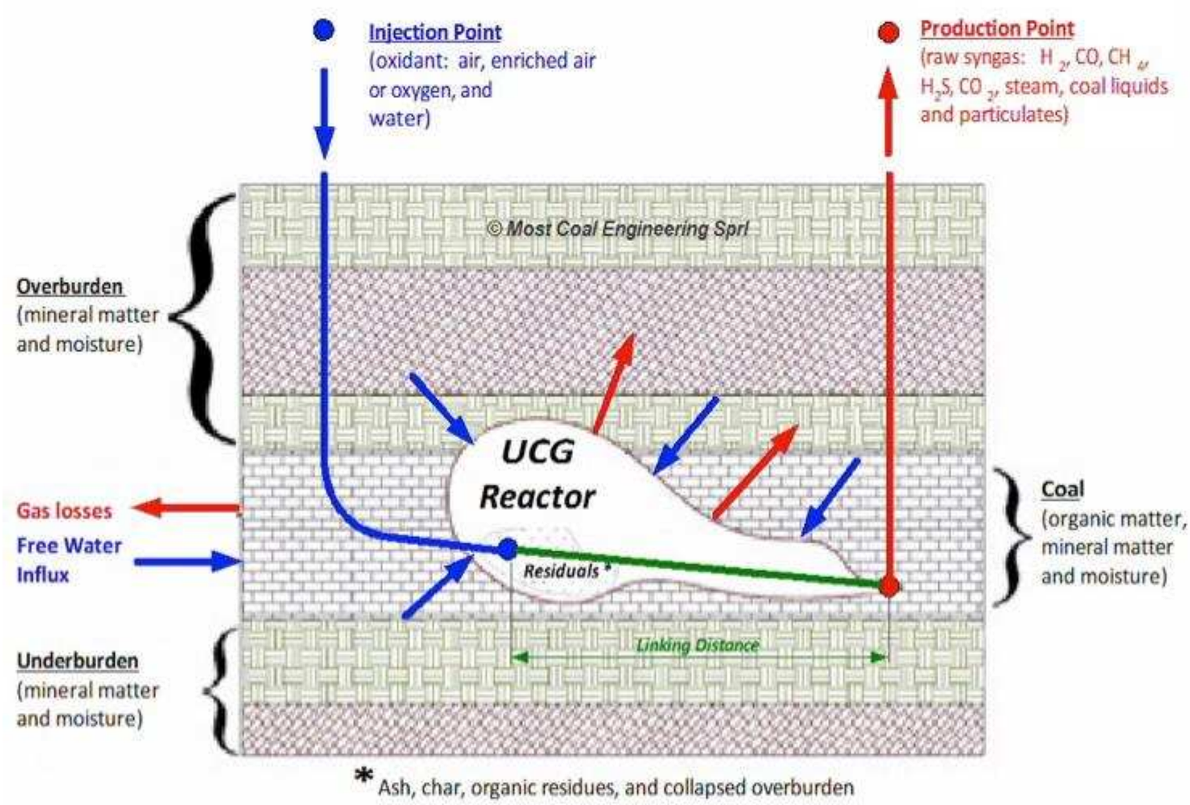
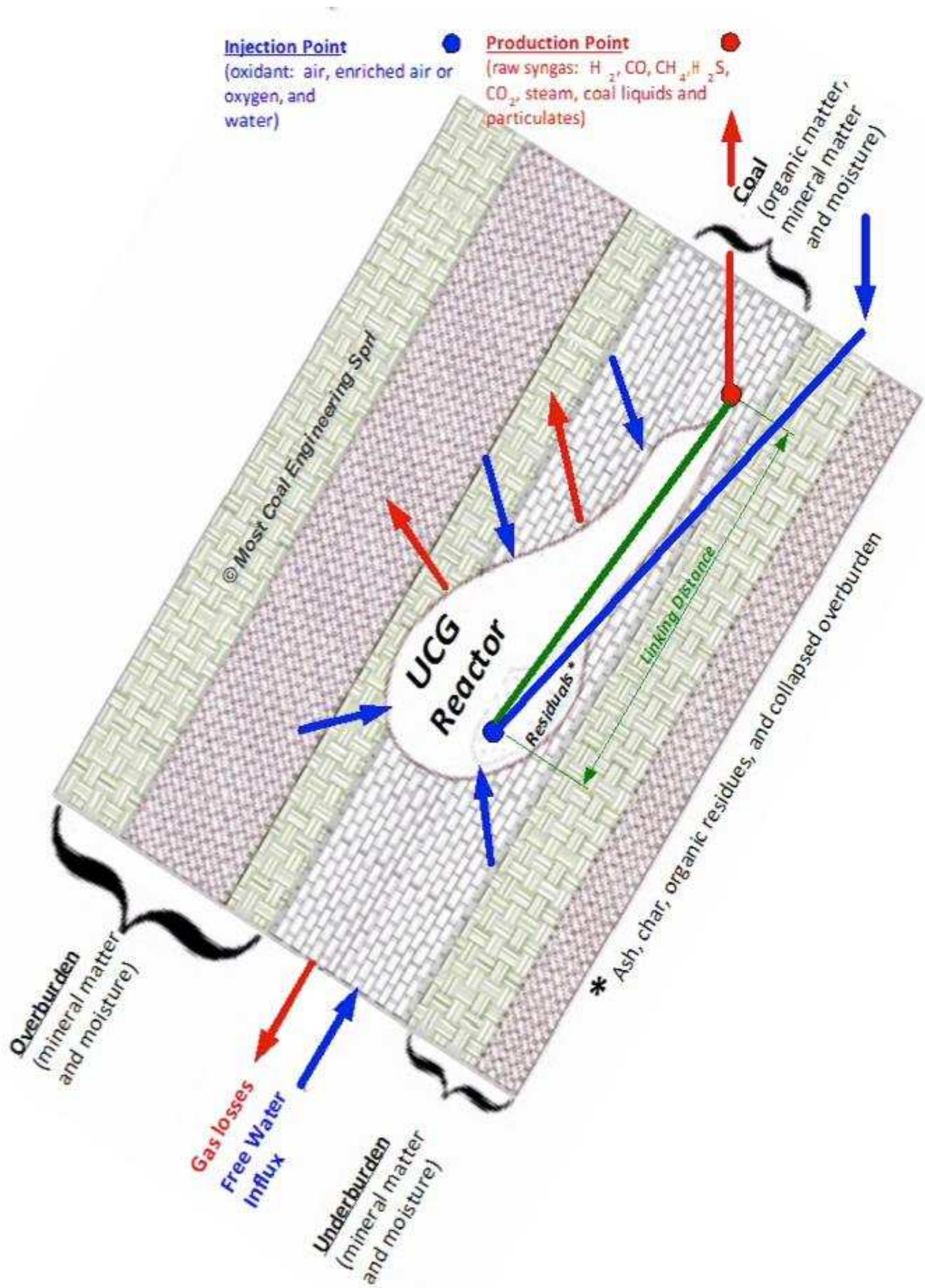


(a) Linked Vertical Well (LVW)



(b) Controlled Retracting Injection Point (CRIP) - Linear



(c) Steeply Dipping Bed (SDB)

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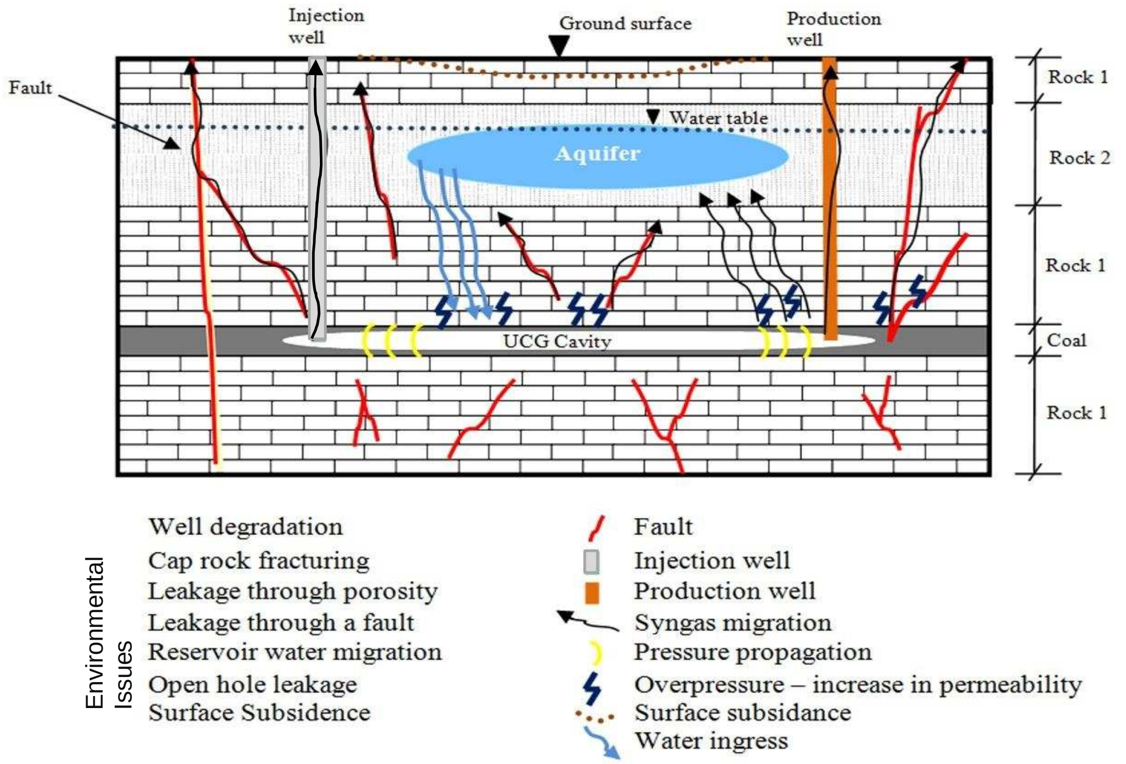

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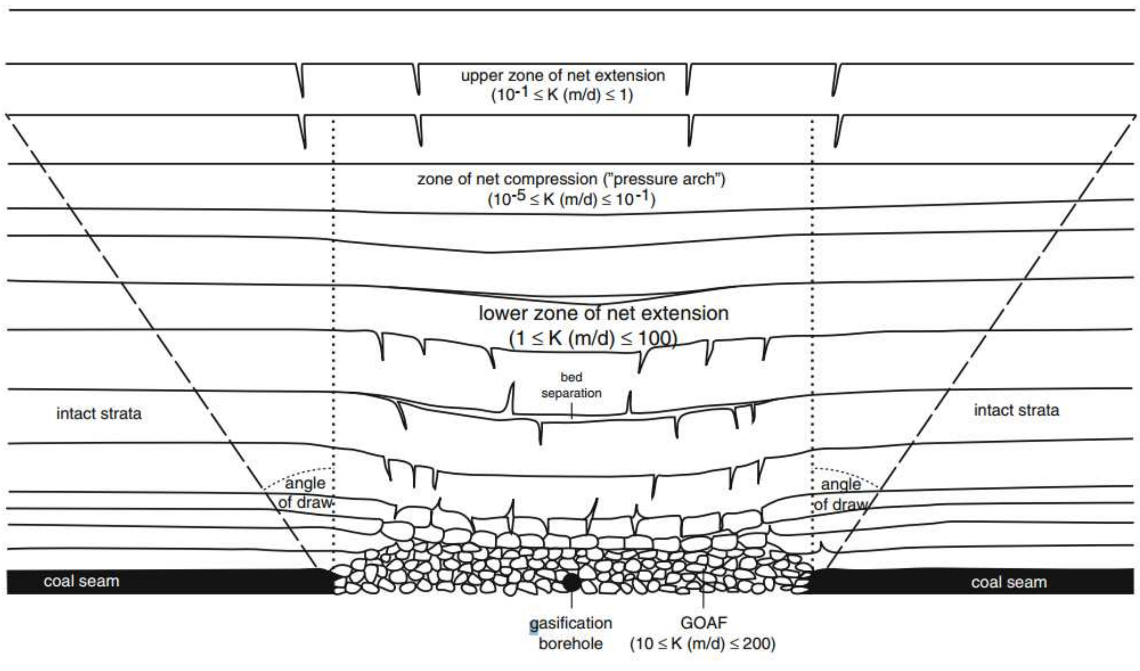

Figure 4. Schematic cross-section showing the impacts of void collapse around a gasification borehole, forming goaf (rubble filling the former void) and overlying zones of extensional and compressional deformation (Younger 2011). The values of K (hydraulic conductivity in units of meters per day) are approximate values derived from a range of literature sources compiled by Younger and Adams (1999).

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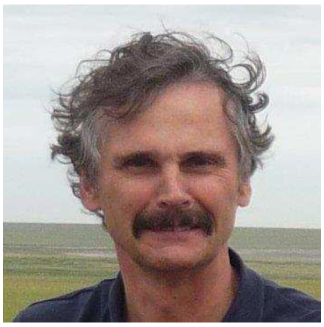

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