Water Management Issues in the Underground Gasification of Coal and the Subsequent Use of the Voids for Long-Term Carbon Dioxide Storage

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Abstract A number of projects around the world are exploring the potential of underground coal gasification (UCG). First developed in Co Durham, UK, in 1912, the technology has since been developed further in the former Soviet Union, the USA, China and Australia. A particular attraction of UCG lies in its suitability for coupling to carbon capture and storage (CCS): we can use our long-standing knowledge of the response of incumbent strata to longwall coal mining to predict substantial increases in permeability in and immediately above the voids created by gasification. As these engineered zones of high permeability will already be connected to surface power plants by the wells and pipelines used to produce synthesis gas during gasification, they represent ideal prospects for permanent sequestration of a large proportion of the carbon dioxide arising. Stored CO_2 will be kept in place by cap rocks higher up in the sequence. In order for the CO_2 to be in the super-critical form, storage zones must be at least 800m below ground. Environmental risk assessment protocols for UCG and UCG-CCS are currently under development, using a combination of process-based modelling of coupled geomechanical, thermal and hydrogeological processes interpreted within an empirical framework derived from more than a century of safe subsea longwall mining. It is shown that the principal risk pathways relate to man-made infrastructure, rather than to cross-measures migration of contaminants through the overburden.

Key Words carbon capture and storage, coal, environment, gasification, groundwater

Introduction

Conventional coal combustion is the least desirable of all fossil fuels from the climate change perspective, yet as oil, gas and uranium ore become increasingly scarce, and renewable technologies still struggle to supply a large proportion of the energy market, coal use is enjoying a global renaissance. Coal reserves available for conventional mining are probably restricted to a couple of hundred years-worth at projected rates of consumption, and these will only be accessed if means are found to achieve carbon capture and storage (CCS). Underground coal gasification (UCG) offers the possibility of exploiting otherwise-unminable seams, potentially increasing global coal reserves by a factor of 3 or more (McCracken, 2008). UCG also offers the possibility of CCS using the subsurface voids which it creates. UCG and CCS technologies are discussed extensively elsewhere (see Roddy & Younger 2010). However, there is almost no literature in the public domain dealing with the ground water issues attending the coupled UCG-CCS process. This paper is a preliminary response to this gap.

UCG and UCG-CCS: the basics

Although pioneered in the UK in 1912, full-scale UCG was first undertaken in the former USSR, and a 100 MW UCG power plant remains in production at Angren (Uzbekistan) today. Numerous pilot operations have taken place in the USA, China and Europe, and commercial UCG operations have recently commenced in Australia. To date, more than 15 million tonnes of coal have been tapped by UCG worldwide (Shafirovich & Varma 2009).

UCG involves gasifying coal in-situ by means of directionally-drilled wells (Roddy & Younger 2010)), using technology developed by the oil and gas industry. The sequence of events involved in UCG is shown in Figure 1. Gasification means 'partial oxidation', and in the case of coal, about 80% of the original calorific value of the solid coal will be present in the resultant gas. Gasification is achieved by spontaneous combustion initiated by injection of steam and oxygen via other boreholes. The operator controls the availability of oxygen and thus the rate of UCG. The result-

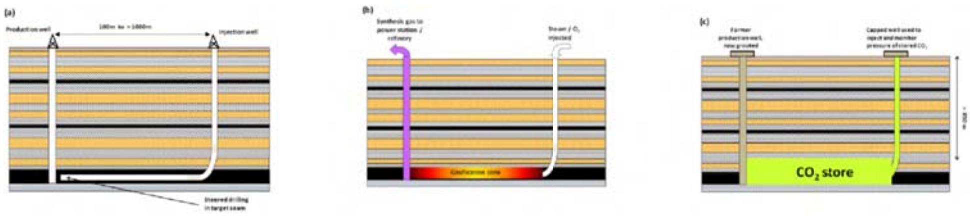

Figure 1 *Three stages in UCG-CCS. (a) Directional drilling of injection and production wells; the two wells do not coalesce, but a small pillar of coal is left between them which is amongst the first coal to gasify. (b) Creation of void by gasification to produce syngas; the gasification zone develops from left to right, progressively consuming coal closer and closer to the injection well as the controlled injection point is retracted from the end of the lateral bore. (c) Sealing of injected CO2 in goaf produced by collapse of void in former gasification zone*

ant hot gas mixture (usually referred to rather loosely as 'syngas') contains hydrogen, carbon monoxide and methane – all of which have significant calorific value. The precise proportions of the various component gases in any particular syngas mixture is a function of depth (= pressure), oxygen injection rate and coal seam quality. The syngas is drawn to the surface via neighbouring production boreholes, whence it can be transported by pipeline for use in a wide range of applications, such as driving turbines to generate electricity or for manufacturing products ranging from diesel to fine chemicals. Indeed, many of the materials needed to construct renewable energy generation plant could be produced from UCG syngas.

Pre- and / or post-combustion clean-up to minimise emissions of SOx and NOx is typically not required for UCG applications, due to the paucity of H_2S and NH_3 in the raw syngas. Gaseous emissions of toxic metals are also generally negligible, as the ash present in the coal remains below ground, and largely avoids fusion. Thus carbon dioxide and water vapour are the only gaseous exhaust streams produced after UCG, which makes the process particularly compatible with CCS. While CO_2 arising from UCG could be disposed of to any geological storage zone, where the UCG process has taken place in seams deeper than about 800m (the depth necessary to ensure pressures sufficient to maintain CO_2 in its super-critical form, which is a pre-requisite for geological storage), the resultant voids and overlying strata have significant potential to store CO_2, offering the appealing prospect of a 'closed loop' in which the energy is released from the coal but the emitted carbon is returned where it came from: deep underground. This closed loop approach is referred to as UCG-CCS.

The voids created by UCG will inevitably collapse, just as voids produced by longwall coal mining do, leaving high permeability zones of goaf which are almost invariably isolated from surface by low permeability superincumbent strata (cf Younger et al. 2002). Where UCG has taken place at depths in excess of about 800m, storage of CO_2 in these artificial high-permeability zones is a very attractive proposition because UCG goaf and the relaxed roof strata above this will typically have permeabilities one to three orders of magnitude greater than those of the most permeable deep saline aquifers or depleted hydrocarbon reservoirs (Younger et al. 2009). With regard to storage capacity, simple density considerations reveal that the void volume needed to store the CO_2 produced from the syngas can be 4 or 5 times the volume occupied by the extracted coal. However, the processes of collapse which produce goaf give rise to enhanced permeability in the immediate roof strata, rendering accessible pore space that was previously unavailable. The zone of enhanced permeability typically extends above the original void roof to an elevation some 15 and 60 times as high as the extracted thickness of coal (Younger & Adams 1999). Above the zone of enhanced permeability a 'pressure arch' forms, in which the strata are in net compression, and thus have permeabilities even lower than those they possessed naturally. This zone of net compression augments the low permeabilities of any shale beds higher in the sequence to form a highly effective hydraulic seal from surface (e.g. Bičer 1987).

Hydrogeological issues in UCG and UCG-CCS
Almost all UCG operations, and certainly all future UCG-CCS operations, are (or will be) located far below the water table. Ground water is therefore a constant presence in and around the gasification zone. Some water is desirable, as it reduces the requirement for steam injection; however, too much ground water entering the gasification zone can hinder ignition. With regard to the ground water body itself, the main risks arising from UCG are:

(i) Ground water depletion: given the high temperatures of UCG zones, any ground water in immediate contact with the coal will tend to vaporise and mix in with the syngas. This will clearly deplete the quantity of water present in the subsurface, though at the depths of relevance to UCG, we would not normally expect the ground water to be fresh; its loss is thus of little or no consequence in terms of freshwater ecosystems or human consumption.

(ii) Ground water contamination: UCG is known to give rise to organic pollutants such as phenols, benzene, polycyclic aromatic hydrocarbons (Liu et al. 2007). As natural ground water will always invade a gasification zone after UCG ceases, UCG will usually have to be restricted to ground water bodies which had been previously classified as permanently unusable (usually on account of high natural salinity). Thankfully, the highly saline ground waters found at depth in most coal basins would indeed fall into this category.

(iii) Gas leakage: permanent loss of syngas into distal ground water is obviously economically undesirable, and UCG is usually conducted at pressures just below hydrostatic to avoid this. Gas leakage is clearly the key issue for CCS in UCG voids. As super-critical CO_2 is one of the most powerful solvents known, it will readily dissolve any pollutants in the former UCG void. Hence the risk assessment for UCG-CCS represents a worst-case scenario for UCG per se: the only important task is to evaluate the risk of CO_2 migration, for if it migrates then the contaminants will certainly migrate with it.

The principles of risk assessment for UCG(-CCS) do not differ in concept from well-established procedures for other forms of coal mining, such as opencast (see Younger & Sapsford 2004). The 'source-pathway-receptor' framework is the key to such assessments. Most of the contaminants produced during UCG are not very soluble in water; however, As a first approximation of the risk analysis, however, Figure 2 presents the possible migration pathways for contaminated CO_2 stored in a former UCG zone.

Abundant experience in areas of former longwall coal mining (Younger et al. 2002) indicates that pathways via virgin rock and thick sequences directly above voids are vanishingly improbable: almost all of the migration of polluted mine waters to surface occurs via man-made infrastructure (e.g. old exploration boreholes, shafts and adits). Fortunately, in UCG operations these

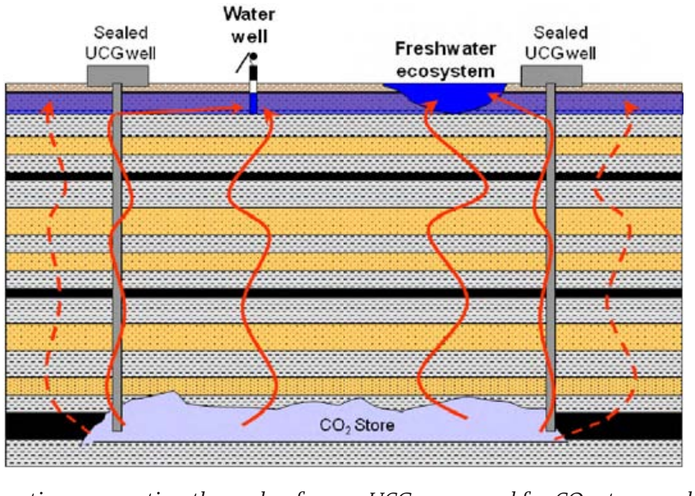

Figure 2 *Schematic cross-section through a former UCG zone used for CO_2 storage showing potential migration pathways to surface waters and ecosystems for stored CO_2. The dashed red lines show the least likely pathways (through undisturbed strata), the solid red lines show the more likely pathways, through disturbed overburden and man-made infrastructure (i.e. sealed wells)*

will be precisely the best-known features, and those most firmly under human control. Since sealed wells represent the preferential pathway for leakage, their integrity has to be assured. That can be done with cement bond logs (Burton 2007; Chadwick et al. 2008). Monitoring of filled and capped boreholes can be used to ensure that no CO_2 leaks are occurring. Indirect monitoring of the gas-filled voids themselves can be undertaken using micro-seismic and micro-gravity geophysical techniques. The mitigation options in the event of leakage include recapping of leaking wells; stopping or reducing further injection; reducing storage or, if all else fails, transferring the CO_2 to another store. Expansive claims for the feasibility of long-term management of boreholes might seem hubristic in the wake of the Deepwater Horizon oil leakage event. However, in the case of UCG, over-pressure (which has given oil in Deepwater Horizon sufficient head to exceed sea level) is not an issue; synthesis gas only exists once formed. Similarly, there is no incentive to store CO_2 at pressures far in excess of hydrostatic. Finally, almost all foreseeable offshore applications for UCG-CCS relate to shallow water (< 50m) settings, where engineering difficulties are far less than at depths in excess of 1.5 km at Deepwater Horizon.

Conclusion

UCG-CCS offers substantial hope for the future, to help society to fully deploy renewable energy technologies without further damaging the atmosphere in the meantime. As with all other forms of coal extraction throughout history however (e.g. Younger & Adams 1991; Younger & Sapsford 2004), UCG-CCS is affected by, and in turn affects, natural ground water systems, and thus by extension poses some risk to surface water systems and ecosystems in hydraulic continuity with affected aquifers. The key to successful implementation of UCG-CCS (and UCG on its own) lies in prudent site selection, respecting the principles of the 'source-pathway-receptor' risk assessment framework which is already in use in the conventional coal mining sector (e.g. Younger & Sapsford 2004).

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