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TECHNICAL ARTICLE

Hydrogeological and Geomechanical Aspects of Underground Coal Gasification and its Direct Coupling to Carbon Capture and Storage

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Abstract Underground coal gasification (UCG) using boreholes drilled from the surface has been feasible for almost a century, but is only now being implemented in market economies. Good analogues for the hydrogeological effects of UCG are provided by longwall mining. Careful planning of UCG void locations and dimensions can result in minimal disturbance of overlying aquifers as close as 40 m above the burn zone. Moreover, development of a pressure arch above the zone of net strata extension can provide a hydraulic seal to prevent vertical fluid migration. Injection of CO_2 into former UCG voids ought to be possible where these are present at depths in excess of $\approx$ 800 m. Analogies to longwall mining suggest that extensional deformation immediately above the burn zone will render sufficient pore space accessible to accommodate all of the CO_2 arising from gasification. In the absence of adequate engineering, the boreholes used in the UCG-CCS processes represent the most likely leakage pathways for injected CO_2. Hence high-quality borehole engineering will be required, taking full account of thermal performance of casing and grout, and geophysical testing of borehole integrity. An agenda for management of groundwater issues at all stages in the life-cycle of UCG and UCG-CCS has been developed, as an *aide memoire* for future developments.

Keywords CO_2 · Coal · Gasification · Groundwater · Storage · Underground

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Coal in a Changing Climate

Of all the fossil fuels, conventional combustion of coal results in the highest atmospheric emissions of carbon dioxide, which is the predominant 'greenhouse gas' implicated in undesirable anthropogenic climate change. Many commentators therefore advocate the urgent abandonment of coal as an energy source. However, as deployment of renewable energy technologies struggles to meet more than a modest fraction of global energy demand (Trainer 2006), as the global peak of oil production looms within the next decade (Strahan 2007), and as global reserves of natural gas and uranium ore place limits of only a few decades on their use for power generation, coal use is actually increasing in order to meet burgeoning energy demands, especially in the fast-growing economies of southern and eastern Asia. Nevertheless, coal reserves available for conventional mining are probably restricted to less than two centuries at projected rates of extraction. However, underground coal gasification (UCG) offers the possibility of exploiting otherwise unmineable seams, potentially increasing global coal reserves by a factor of 3 or more (McCracken 2008). UCG also offers the prospect of carbon capture and storage CCS using the subsurface voids which it creates (Roddy and Younger 2010). If this can be achieved, then the energy locked up in coal could be accessed without making any further contribution to climate change. This potentially offers an attractive window of opportunity for the improvement and deployment of renewable energy technologies, which will in any case be needed in the future after all other options are exhausted.

Achievement of sustained, industrial-scale deployment of UCG, with or without CCS, will require that a number of challenges be overcome over the next few years.

Effective management of groundwater in and around UCG operations is amongst the greatest of these challenges. However, it has been noted that there is a dearth of information on UCG in the open literature (Couch 2009), presumably reflecting commercial sensitivities, and it is therefore unsurprising that there is as yet very little publicly available information on groundwater management in and around UCG voids, let alone on UCG voids used for CCS. The history of conventional coal mining teaches us that an earlier appreciation of hydrogeological processes affecting extraction activities could have prevented the loss of valuable coal reserves to flooding, and indeed would have spared thousands of lives. While UCG is not as inherently hazardous to human life as conventional underground coal mining, it can be expected to be just as economically sensitive to poorly managed groundwater conditions. As a new industry which is set to reach maturity in the twenty first Century, it is inconceivable that UCG(-CCS) will be allowed to develop without scientifically-based groundwater management plans and procedures. This paper is intended to provide a basis for the development of these, through a generic exploration of the hydrogeological implications of UCG, culminating in a summary which can be used as the basis for developing site-specific conceptual models and hydrogeological risk assessments to support particular UCG(-CCS) developments in the future.

Summary of the UCG Process

UCG procedures have been extensively described in a number of recent publications (e.g. Couch 2009; Roddy and Younger 2010; Shafirovich and Varma 2009; Younger et al. 2010a, b, 2011); hence, only a brief summary is given here. The UCG process commences with the steered drilling of boreholes into target coal seams (Fig. 1). A minimum of at least two boreholes are generally required to initiate UCG. Both are initially drilled down vertically. Beyond this point in the procedure, a number of variant approaches can be pursued; in the description which follows, the focus is on the most popular current variants. One of the vertical boreholes (the future production borehole) will initially be continued in vertical orientation all the way to the target coal seam. The other borehole (destined to be an oxidant injection borehole) will typically be deviated towards the horizontal by steering the drill bit (a number of patented procedures exist for doing this; Couch 2009). Once the steered drill bit has entered the coal seam, it can be extended laterally for substantial distances (from several hundred meters to a kilometer or more), staying within the coal seam as far as possible. This can be achieved by suspending an electromagnetic source at the seam horizon in the vertical production borehole, and then having a sub-horizontal 'lateral' drilled from the injection borehole 'home in' on the electromagnetic signal. In order to avoid futile injection of oxidants during the early phases of gasification, the lateral section of the second borehole is typically terminated a few meters from the borehole with the electromagnetic source, so that a small pillar of coal remains between the two.

In any one area, an array of injection boreholes will converge on a single production borehole, which might itself be extended laterally through the seam for a kilometer or more (Fig. 1). Once a full suite of boreholes is complete, a flexible alloy pipe with an open-ended gas injection valve is inserted into each injection borehole in turn. This injection device is usually termed a CRIP,

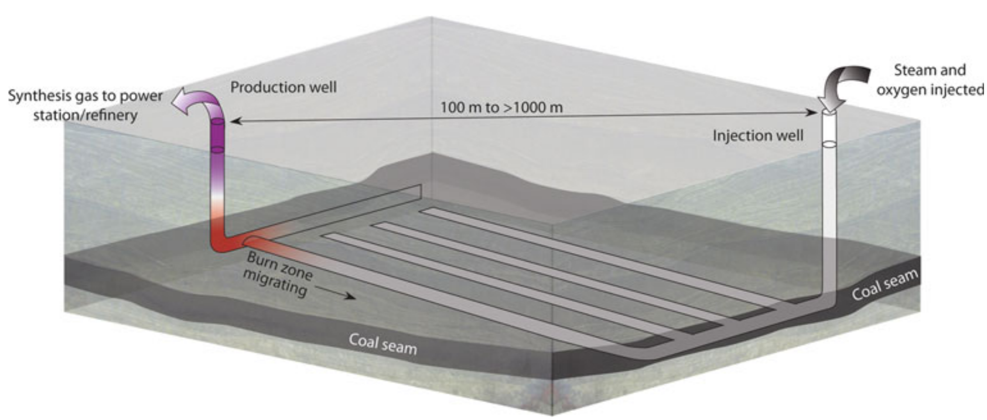

Fig. 1 Schematic block diagram showing a typical layout of injection and production boreholes for an underground coal gasification (UCG) operation (not to scale). For simplicity, only a single coal seam is shown. In real operations, multiple seams may be gasified in parallel or in sequence. As each of the sub-horizontal lateral sections of the injection boreholes are used to develop burn zones, voids develop in the coal seam, which can then be expected to collapse, forming goaf (see Fig. 2)

standing for ‘controlled retractable injection point’ (Burton et al. 2006). When a mixture of oxidant gases is injected through this pipe, the coal at the end of the injection borehole can be made to ignite, partially oxidizing the surrounding solid coal so that it is transformed into a gas phase, which will typically contain as much as 80% of the energy content of the original solid coal (Couch 2009). (Oxygen is preferable to air as the oxidant gas, as use of air results in a lower heating value and higher NO_x content in the produced gas). Steam is sometimes added to the injected gas stream, as this favours the liberation of hydrogen during the gasification process (see below).

The gas resulting from UCG is generally referred to, rather loosely, as synthesis gas, or ‘syngas’ for short. (Strictly speaking, syngas is a mixture of hydrogen and carbon monoxide, though in the case of UCG, the resultant gaseous mixture usually also includes some methane and carbon dioxide). Once the pillar of coal that separates the injection borehole lateral from the production borehole has been breached, syngas will migrate to the surface through the production borehole. When syngas production is underway, the CRIP is gradually retracted, so that portions of coal ever further from the production borehole are progressively gasified. Retraction of the injection pipe can be achieved either by reeling it back along the lateral, or else using special tools to cut off and abandon sections of it. Thus, the active ‘burn zone’ gradually migrates away from the production borehole. The gasification process is readily controlled by restricting the rate of oxygen injection.

Clearly, UCG should only be undertaken at depths great enough to avoid inducing uncontrolled ingress of oxygen from the surface via migration along coal cleats from seam outcrops, or via cracks that reach the ground surface above the burn zone. This is best achieved by ensuring that UCG takes place far below the water table. Otherwise, there is a risk of uncontrolled oxygen ingress occurring, potentially supporting a wildfire in the coal seam, which is highly undesirable (Stracher et al. 2002).

UCG has been achieved using variants of the methodology outlined above for almost a century, since the first proof of the concept in County Durham, England, in 1912 by Sir William Ramsay, who is better known as the discoverer of the Noble Gases. Industrial-scale UCG was first undertaken in the former USSR, and a 100 MW UCG power plant remains in production today at Angren (Uzbekistan) (Couch 2009). Numerous pilot operations have taken place in the USA (e.g. Boysen et al. 1990; Oliver 1987), 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 and Varma 2009).

Geomechanical and Hydrogeological Impact of UCG on Overlying Strata

Despite its direct relevance to important issues such as management of UCG-induced land subsidence, surprisingly little discussion of this key topic has appeared in the open literature to date (see the review of Couch 2009, for instance). The following discussion is therefore derived analogically from the wealth of literature on similar processes that occur during longwall mining (Booth 2002; Brady and Brown 1993; NCB 1975; Younger et al. 2002). Before proceeding with this discussion, it is worth noting that the analogy between longwall and UCG is not perfect: for instance, incomplete burning between adjoining borehole laterals (Fig. 1) will result in pillars of intact coal being left behind. In relatively shallow settings, these pillars might offer some resistance to overburden collapse, so that bord-and-pillar mine workings might be a better analogy than longwall panels. However, as recent experiences at the Cougar trial site in Queensland illustrate (Moran et al. 2011), UCG at relatively shallow depths ($\leq$300 m) will likely not be an attractive option from an environmental management perspective. In the deeper settings in which most future UCG activity is anticipated, residual pillars are much more likely to collapse, and to do so more rapidly than in longwall mining, given the absence of the artificial face supports routinely used in the latter. However, where face supports are essential in situations where access must be maintained for humans and large machines such as drum shearers, injected gas can be expected to migrate to combustion locations even after substantial collapse.

It is also worth noting that generic longwall mining analyses—including the relatively simple geometric scenarios analyzed below—tend to address relatively low-dip settings in which assumptions of planar strain development allow a two-dimensional solution to be applied. More complex settings, arising from high strata dips and/or irregular burn zone geometries, require case-specific analysis, taking fully three-dimensional strain patterns into account. Such analysis is beyond the scope of the present paper.

Having recorded these reservations, some a priori consideration of the geomechanical behaviour of UCG operations can now be developed by analogy to longwall operations in relatively flat-lying strata. The UCG process leaves behind voids in the coal seam. As neighbouring laterals from injection boreholes are used as burn zones (Fig. 1), an array of parallel voids will be created, with thin pillars of coal separating them. These voids will inevitably collapse, just as voids produced by longwall coal mining do. The result is that the voids fill with a breccia of roof debris, which is usually known as ‘goaf’ in the UK (derived from '*ogof*', the Welsh word for a cave; this word has become 'gob' in North American parlance). In the strata overlying the goaf, a zone of extensional deformation develops, which is manifest in the sagging and cracking of individual beds, and the development of bed separation hollows between suprajacent layers (Fig. 2). This zone normally extends to a height equivalent to about a third of the width of the extracted zone below. Higher still, the zone of extensional deformation is overlain by a zone of net stratal compression, sometimes termed the 'pressure arch', in which beds are squeezed more tightly together than was the case before mining began. Higher still, the pressure arch tends to be overlain by a further zone of net extension, which will often extend all of the way to the surface (Booth 2002; Dumpleton 2002). Both the zone of net compression and the uppermost zone of net extension tend to be about as thick as one-ninth of the width of the zone of coal extraction (Younger and Adams 1999).

This deformational stratification above a collapsed void is reflected in the development of distinct zones of permeability (Fig. 2). The goaf itself is usually rather permeable, as is the immediately overlying zone of net extensional deformation. This zone typically extends above the original top of the seam to a height equivalent to as much as sixty times the thickness of the coal extracted (Younger and Adams 1999). Within this extensional zone, dilation of pre-existing fractures (and development of new ones) results in permeable pathways that allow fluids access to the pore space of sandstones and other permeable lithologies, so that the total pore space made available by the goafing of UCG panels can be expected to significantly exceed the volume of coal extracted (Booth 2002). Higher still, in the pressure arch, net compression usually diminishes permeabilities (which will already be very low in the case of mudstones and siltstones), thus developing an effective hydraulic seal separating the goaf and extensional zone from overlying water bodies or the ground surface (e.g. Bičer 1987; Booth 2002; Orchard 1975; Singh 1986; Singh and Atkins 1983). Above the pressure arch, a further zone of net extension usually develops (Booth 2002; NCB 1975), in which significant increases can be induced in the permeability and storativity of shallow aquifers (Dumpleton 2002). Nevertheless, the deeper-lying pressure arch (Fig. 2) still tends to isolate these enhanced aquifers from the zone of total extraction at depth (Booth 2002; Dumpleton 2002). Exceptions can occur where the outer limit of the zone of deformation (defined by the so-called 'angle of draw' shown on Fig. 2) intersects a major fault or igneous dyke, which can provide short-circuited hydraulic connection from deep to shallow strata (Booth 2002; Dumpleton 2002).

A large body of empirical evidence from the UK (NCB 1975) was used to develop a criterion for safe longwall mining beneath water bodies, observance of which has

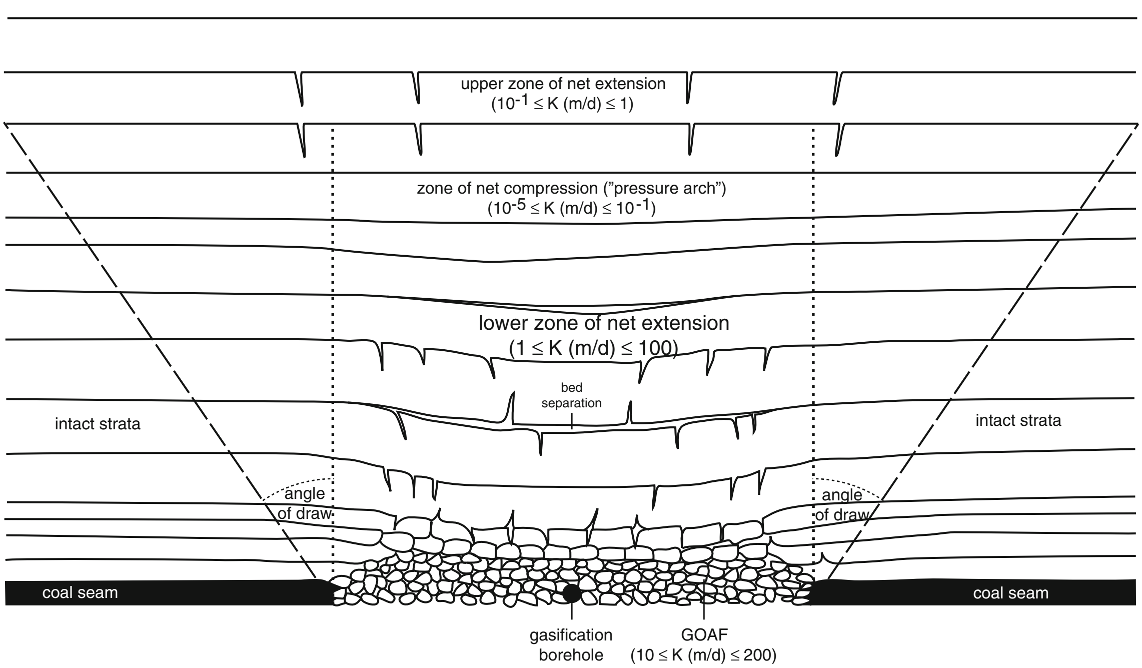

Fig. 2 Schematic cross-section showing the impacts of void collapse around a gasification borehole, forming goaf (rubble filling the former void) and overlying zones of extensional and compressional deformation. The values of K (hydraulic conductivity in units of meters per day) are approximate values derived from a range of literature sources compiled by Younger and Adams (1999). The angle of draw delimits the outer edge of the zone of strata deformation, and will often display values of around 35° from the *vertical*, though this will vary depending on lithology, *thicknesses* of different lithological units, presence of faults etc

been vindicated by a record of extensive subsea longwall mining for more than a century without a single case of seawater inrush to the workings. The current UK criterion for safe longwall mining beneath water bodies specifies a maximum induced net tensile strain at the base of any overlying aquifer of 10 mm per meter (Orchard 1975; Singh and Atkins 1983). Calculation of net tensile strains as a function of void width, thickness of cover to the nearest overlying aquifer, and other parameters was described in detail (NCB 1975). This modelling procedure can be used to predict the likelihood of UCG void collapse inducing groundwater inflows from aquifers at various heights above the gasified seam—a process with important implications both for the progress of gasification and for any subsequent isolation of contaminants or injected gas (e.g. CO_2) in the resultant voids. Figure 3 shows the relationship between net tensile strain at the base of an aquifer overlying a UCG zone and the thickness of strata separating the two, for a range of possible UCG burn zone widths. The dynamics of burn zone development mean that the width of the void created by gasification using any one borehole will typically be less than 30 m (Couch 2009). This is far narrower than most longwall panels, and is in fact typical of 'shortwall' retreat face designs in circumstances where avoidance of induced inflow of groundwater is a priority (see, for instance, the summary of experiences at Wistow Colliery in the Selby Coalfield, UK, given by Dumpleton 2002). In most UCG applications, successive parallel in-seam reaches of injection boreholes will be used for gasification, producing voids separated by narrow pillars of unburned coal. These pillars can be expected to yield, becoming crushed during later goafing. In this manner, coalescence of the burn zones of up to six parallel injection boreholes can produce composite panels with widths totalling as much as 200 m (cf Couch 2009, p. 113). The modelling algorithm used to produce Fig. 3 includes some asymptotically bounded quadratic laws, which lead to some complexities in predicted behaviour for small values of void width and strata thickness. However, it is evident that, irrespective of void width, net tensile strains in excess of 10 mm/m will not be induced where there is more than 60 m of cover separating the UCG burn zone from the nearest overlying aquifer; indeed, for narrower void widths, this should remain true for cover thicknesses of as little as 40 m.

Hydrogeological Processes Occurring During UCG

Given the current and anticipated economics of coal production, established opencast and deep mining methods will almost always be cheaper than UCG for seams shallower than about 500 m. For this reason alone, UCG is best reserved for the exploitation of deeper seams, which will almost always be far below the water table. Nevertheless, in the past, some UCG experiments have been conducted above the water table (either the natural water table or a water table depressed by active mine dewatering; Couch 2009); some of these experiments notoriously led to pollution of shallow groundwater resources (e.g. Couch 2009; Liu et al. 2007), and also ran the risk of igniting uncontrolled seam fires. Avoidance of these two hazards provides ample motivation for ensuring that future industrial-scale applications of UCG be developed far below the water table, preferably in zones where the groundwater is naturally too saline for potable or agricultural use. High hydrostatic pressures around a UCG burn zone can provide an effective barrier against the escape of syngas (Couch 2009). This is not only important economically; it also prevents gas migration to the surface where it might give rise to surface hazards (cf Robinson 2000). Furthermore, the efficiency of gasification processes increases with pressure (Couch 2009).

For these reasons, management of groundwater is likely to be a major consideration in future UCG developments. At the simplest level, it is essential that borehole design and development takes into account the necessity of casing-out shallow aquifers, so that evacuation of UCG production boreholes can be achieved relatively easily, allowing free passage of produced syngas. With regard to the UCG process itself, groundwater plays an ambiguous role. Where too much water is present in the burn zone, coal ignition can be hindered as thermal energy is unnecessarily wasted on vaporizing water. Even when ignition is achieved, the resultant syngas will contain too much water vapour, thus reducing its bulk heating value. This happened, for instance, in the UCG trial at Teruel in Spain in the late 1990s, where the gasified seam immediately underlies a prolific aquifer. Ignition and maintenance of the burn proved difficult, and the resultant syngas contained about 50% water vapour by volume (Couch 2009, p. 57).

On the other hand, some steam is required during UCG to drive the following reactions to the right (both are endothermic in that direction, so the heat in the steam is also consumed):

$$C_{(S)} + H_2O_{(g)} \rightleftharpoons H_{2(g)} + CO_{(g)} \quad (1)$$

$$CO_{(g)} + H_2O_{(g)} \rightleftharpoons H_{2(g)} + CO_{2(g)} \quad (2)$$

Consequently, a modest ingress of groundwater to the burn zone—in which the water will quickly vaporize to steam—can reduce the need for steam injection from the surface, saving money and reducing potential workforce hazards (Couch 2009).

The overall UCG process is strongly exothermic, and temperatures in the burn zone are likely to occasionally

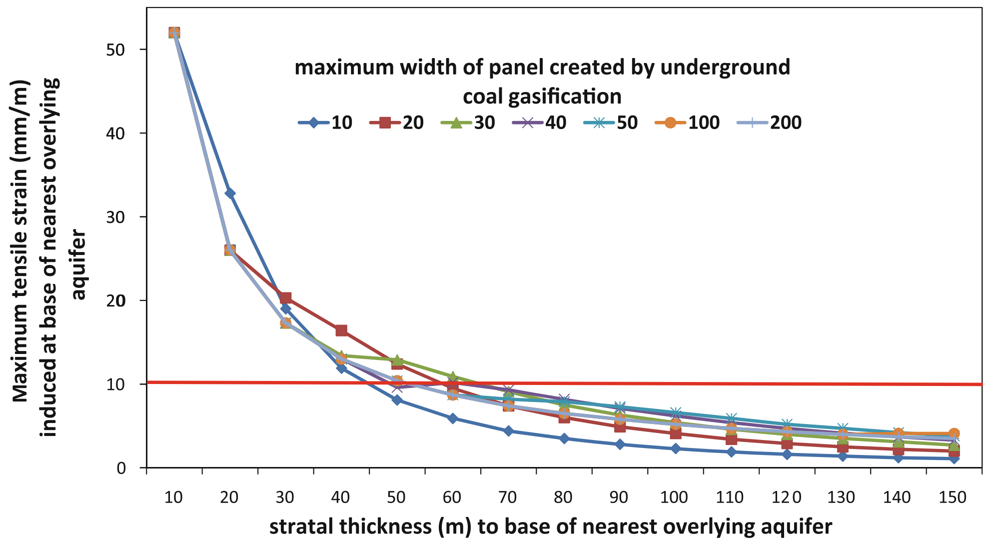

Fig. 3 Predicted values of net tensile strain at the base of an aquifer overlying a zone of UCG goaf development, as a function of the thickness of the intervening strata between the original seam roof and the base of the aquifer. Calculations of tensile strain were made according to the methodology of NCB (1975). The particular scenario modelled here assumes a seam of 2 m thickness, with a total subsidence to thickness ratio of 0.8. A variety of widths for the zone of UCG goaf developed around one or more parallel boreholes is shown. A single borehole would generally be expected to achieve a width of around 30 m, with greater total widths resulting from collapse of adjoining burn zones (cf Fig. 1)

exceed 900°C. Even after cooling (through conductive heat loss to surrounding strata and convective heat loss to native groundwater), syngas typically flows through production wells at temperatures between 200 and 400°C (Couch 2009). Around the burn zone, the high buoyancy of hot syngas relative to groundwater will tend to lead to large pores getting invaded with bubbles of syngas, which will heat the groundwater and turn it into steam. A dynamic interface between steam and hot groundwater will develop around the UCG burn zone, in which steam will mix with the syngas.

Steam not consumed in reactions (1) and (2) above may eventually report to the production borehole (Fig. 1). Strictly speaking, the conversion of natural groundwater to steam in a UCG burn zone is a consumptive use of water resources, although in the majority of cases, the water in question will have been too saline for potable or agricultural use anyway, and the total quantities involved will be rather modest, as the UCG operator has a vested interest in minimizing the proportion of steam in their syngas. One of the disadvantages of UCG is that precise control of process conditions is very difficult; only the oxygen supply can be controlled directly from the surface. Hence, minimization of steam production from groundwater is critically dependent on making a sound choice of seam in the first place, avoiding those which are surrounded by excessively prolific aquifers.

Getting the balance right between too little and too much groundwater ingress is likely to prove a recurrent challenge in industrial-scale UCG operations. However, from the foregoing account of the geomechanical/hydrogeological response of strata to UCG void collapse, it seems appropriate to recommend as an a priori guideline that water conditions during gasification are likely to be favourable where void collapse will not induce net tensile strains in excess of 10 mm per meter at the base of any aquifers higher in the coal-bearing sequence. In practical terms, this means that one should ensure a vertical interval of between 40 and 60 m between a UCG burn zone and any such aquifers. As experience with UCG operations accumulates in a region, a posteriori analysis can be used to ascertain whether a lowering of this net tensile strain criterion can be tolerated.

If large-scale depletion of groundwater resources is unlikely to be a major issue in UCG, groundwater contamination is potentially more challenging. UCG is known to give rise to organic pollutants such as phenols, benzene, and polycyclic aromatic hydrocarbons (Liu et al. 2007; Moran et al. 2011). Fortunately, as these compounds are very dense compared to syngas, they tend to remain behind in the burn zone. Furthermore, these cyclic compounds are generally poorly soluble in water, so that they will not dissolve very readily in the groundwater that will inevitably flood a former burn zone after gasification ceases. Nevertheless, under European law, almost any dissolution of such compounds in groundwater could be deemed to constitute pollution (cf Younger and Sapsford 2004), This is another reason why UCG is best undertaken in deep strata containing permanently unusable saline groundwaters.

CCS in UCG Voids: A Hydrogeological Perspective

Underground storage of gas has a long pedigree, and it has been conducted successfully for more than 60 years in voids originally developed by solution mining of evaporite minerals using borehole injection-recovery infrastructure not dissimilar to that required for UCG. To date, most underground storage of gas has focused on methane and hydrogen—which, as potentially explosive, highly flammable gases are in many ways more challenging to handle than CO_2. A thorough review of global experiences to date with geological storage of gases is given by Evans and Chadwick (2009).

CO_2 can only be stored effectively in sedimentary rocks if it is compressed sufficiently for it to assume its super-critical form, in which it has the density of a liquid but retains the compressibility of a gas (IPCC 2005). As litho- and hydro-static pressure both increase with depth beneath the Earth's surface, the pressure required to maintain CO_2 in its super-critical form corresponds to a minimum depth of subsurface storage. For pure CO_2, this equivalent depth is around 650 m. However, given that CO_2 derived from industrial sources (e.g. power station flue gas) will not be pure, the minimum depth requirement for storage will be somewhat greater than this, perhaps exceeding 800 m. There are many coal seams thick enough for UCG at depths in excess of 800 m, and as these would typically be too deep for conventional mining under current and reasonably foreseeable economic conditions, such a minimum depth requirement for UCG-CCS would have the happy side-effect of avoiding any direct competition between UCG and conventional mining operations.

It is apposite to ask how the permeabilities of goaf and the overlying extensionally-deformed strata compare with those of depleted hydrocarbon reservoir rocks or deep saline aquifers, which are the most common targets for geological CCS projects. Table 1 compares typical permeabilities of oil/gas reservoirs (and thus of deep saline aquifers, which are effectively reservoir rocks that do not contain hydrocarbons; IPCC 2005) with permeabilities of goafed zones formed during longwall mining. By direct analogy, we can expect UCG goaf and overlying roof strata to develop permeabilities between one and three orders of magnitude greater than those associated with the most permeable hydrocarbon reservoirs/deep saline aquifers. Storage of CO_2 in these zones of artificially high permeability is thus a very attractive proposition (Younger et al. 2011).

However, permeability is only one of the crucial parameters that determine the viability of CO_2 storage in a given rock mass. The effective porosity of the rock is also important. In the case of UCG, given that solid coal is relatively pure carbon, whereas the gasification process adds two oxygen atoms to each carbon atom to produce CO_2, the pore volume needed to store supercritical CO_2 derived from coal gasification will typically be about four times greater than the volume originally occupied by the solid coal (Younger et al. 2010a, b). Thus, while we can reasonably expect most of the volume of extracted coal to be preserved as pore space in goaf formed by collapse of the UCG voids, this will not on its own provide sufficient volume to store all of the CO_2 produced. As noted above, however, the zone of extensional deformation above a goafed panel typically extends above the seam to a height equivalent to as much as 60 times the thickness of the coal seam (and never less than 15 times). The sum of the pore space in the goaf and in this disturbed profile of overlying strata provides an estimate of the total volume of storage available to accommodate injected CO_2. Figure 4 shows how far above the original seam roof the deformation zone must extend to accommodate all of the CO_2 generated by gasification of the coal. This 'accommodation profile' for CO_2 is expressed as a multiple of the seam thickness (to which it is far more sensitive than it is to void width), and it obviously varies with the effective porosity of the overlying strata. As Fig. 4 shows, for all porosities of 5% or greater, the accommodation profile resulting from goafing falls within the limit of 60 times seam thickness noted above. This 5% porosity is relatively modest compared with values actually encountered in many coal-bearing sequences. For instance, analysis of sandstones from the coal-bearing Carboniferous succession of the Northumberland Basin, UK (Younger 1992), yielded intergranular porosity values averaging 13% (standard deviation 5%; n = 13). To these must be added fracture porosity of several percent (both natural and that induced by goafing). For values of total porosity around 15% suggested by these considerations, the relationship shown in Fig. 4 suggests that all of the CO_2 produced could be accommodated within a profile equivalent to only 20 times the original seam thickness.

A final factor in determining the viability of CO_2 storage in former UCG zones and fractured overlying strata is the presence of 'cap rock' conditions above the CO_2 storage zone, to prevent migration of injected CO_2 back to the atmosphere. As previously noted, a pressure arch typically develops above the zone of extensional deformation overlying goaf (Fig. 2). This pressure arch provides an effective barrier to vertical fluid migration (see, for instance, Booth 2002; Dumpleton 2002; Orchard 1975; Singh and Atkins 1983; Younger et al. 2002). Once again, application of the strata deformation model developed from longwall mining (Fig. 3) suggests that low net tensile strains (and thus low permeabilities) are likely to develop at heights of 100 m or more above the UCG goaf. A note of caution is warranted here, however; while the pressure arch may result in a

Table 1 Comparison of typical permeabilities (in darcies) of oil/gas reservoirs (and thus of deep saline aquifers) and goaf formed by total collapse of extracted voids in coal (after Younger et al. 2011)

Permeabilities of oil and gas reservoirs, and of deep saline aquifers		Permeabilities of goaf from longwall mining (analogues for those formed by UCG)	
Poor reservoir	0.001–0.01	With mudstone roof strata	1–10
Good reservoir	0.01–0.1	With thinly interbedded silt- sand- mud- stone roof strata	10–50
Excellent reservoir	0.1–1	With strong sandstone/limestone roof strata	20–500

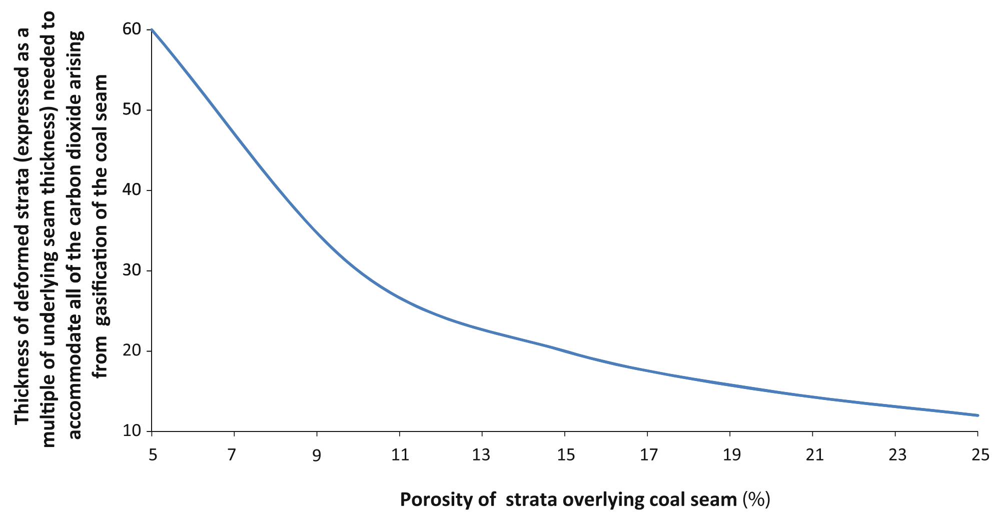

Fig. 4 The total thickness of deformed strata overlying a gasified coal seam that would be needed to accommodate all of the CO_2 arising from that seam (which would have to be injected after syngas use), as a function of the mean porosity of the strata. Thickness is expressed as a multiple of the original thickness of the gasified seam

permeability low enough to contain injected gas during UCG operations, it cannot be assumed that the same will apply at the much higher pressures relevant to CO_2 injection. In many cases, active reservoir pressure management (by pumping of brine displaced by injected CO_2) might well be necessary to avoid exposing the cap rock horizons to excessive stress (e.g. Buscheck et al. 2010).

It was previously noted that UCG yields some cyclic organic compounds, which are generally regarded as contaminants. Although these compounds are sparingly soluble in water, super-critical CO_2 is one of the most powerful solvents known, and it will readily dissolve them. On reflection, however, this apparently unfavourable circumstance has an advantage when it comes to risk assessment for UCG-CCS. Since any contaminants arising from UCG can be assumed to dissolve in CO_2, then risk assessment for the migration of these contaminants is essentially the same task as assessing the risk of CO_2 migration. This considerably simplifies the workload for hydrogeologists.

Key issues in risk assessment for CCS in general were discussed by Chadwick et al. (2009), and the particular issues arising in relation to CCS storage in former UCG zones were summarized by Younger et al. (2010a, b). The low vertical permeabilities of most coal-bearing sequences of strata effectively preclude long-distance migration of polluted water, syngas, or injected CO_2 via 'cross-measures' flow through intact strata, or indeed through strata deformed by collapse above UCG goaf. In the latter case, this is due to the development of the 'pressure arch' discussed previously, as well as to the widespread occurrence of mudstones in coal-bearing sequences. Vertical migration via permeable fault planes is a greater risk, and care must be taken to evaluate this carefully wherever faults might be intersected by the angle of draw (Fig. 2) around a UCG goaf zone.

While many risk assessments for CCS appear to have focused on the integrity of cap rocks and other stratigraphic/structural barriers to gas migration, a review of safety incidents associated with underground storage of methane highlights the importance of taking full account of potential migration pathways associated with borehole infrastructure (Miyazaki 2009). This aligns with abundant experience of mine water migration in areas of former longwall coal mining (Younger et al. 2002), which has shown time and time again that most undesired fluid flow occurs via man-made infrastructure (e.g. old exploration boreholes, shafts, and adits). Fortunately, in UCG-CCS operations, boreholes will be precisely the best-known features, and those most firmly under human control. In the wake of the 2010 oil leakage event at the Deepwater Horizon borehole site in the Gulf of Mexico, it might seem hubristic to claim that management of boreholes can ensure the prevention of undesirable outcomes, but it is important to realize that UCG settings are not subject to the phenomenon of hydrocarbon over-pressure that led to the reservoir at Deepwater Horizon having a total hydraulic head greater than hydrostatic. Syngas only forms when oxygen is injected. Similarly, there is no incentive to store CO_2 at pressures far in excess of hydrostatic—albeit low permeabilities may necessitate high injection rates to overcome resistance. In such cases, active pressure management techniques may have to be deployed (e.g. Buscheck et al. 2010), but had a secondary well been available in the Deepwater Horizon system, immediate pressure management could have been employed to minimise the spillage. Finally, almost all foreseeable offshore applications for UCG-CCS relate to shallow water (<50 m) settings, where engineering difficulties are far less than at depths in excess of 1.5 km at Deepwater Horizon. Perhaps a more relevant example of successful management of deep boreholes is provided by another famous incident in 2010: the rescue of 32 miners from the San José mine at Copiapó in Chile, in which a directionally-drilled well was completed at large diameter to millimeter accuracy at record speed (Shoup and Lips 2010), effectively dealing with groundwater by means of rapid casing. Nevertheless, UCG-CCS raises some particular challenges for borehole engineering, which are briefly explored below.

Borehole Engineering Issues in UCG-CCS

Boreholes drilled and completed for purposes of UCG(-CCS) need to completely isolate the borehole interior from shallow aquifers above the UCG target seam(s). This is not only to ensure that no contamination of usable groundwater can occur; it is also essential for production purposes, to prevent loss of injectant gases or produced syngas to other strata. As such, the integrity of casing and grouting are of paramount importance. Nevertheless, very little discussion of borehole engineering issues for UCG(-CCS) has yet appeared in the open literature (see Couch 2009, p. 43). From a practical point of view, vertical boreholes are far easier to case and grout effectively. Therefore maintenance of verticality until the deepest potentially vulnerable aquifer has been passed is very important. Thereafter, steered drilling can be used to complete the injection and production boreholes with in-seam laterals, as shown in Fig. 1.

Temperature is the most important variable to consider in relation to borehole integrity in UCG(-CCS) operations. While some UCG operations reportedly use the same boreholes for both injection and production at different times (Couch 2009), the large difference in maximum temperature between the two modes of use suggest that bespoke designs might well be more cost-effective. Injection boreholes will usually operate well within the temperature ranges routinely encountered in oil and gas borehole operations; even where steam injection is practiced, UCG injection boreholes will not experience temperatures much in excess of about 120°C. Super-critical CO_2 will typically be cooler than this too (though generally in excess of 25°C).

On the other hand, UCG production boreholes will typically experience far higher temperatures, typically up to 400°C (and even as high as 900°C for short periods). These temperatures are significantly higher even than those typically encountered in high-enthalpy geothermal borehole applications. Careful consideration of materials behaviour at high temperatures is therefore warranted when designing boreholes for UCG production service. Two main components of boreholes are likely to undergo significant changes in strength and continuity when subjected to temperatures oscillating by as much as 400°C: steel casings and the cement-based grouts that seal the annulus between the casings and the surrounding rock mass. With regard to steel, strength reduction appears to be modest for temperatures up to about 300°C, but will reduce by as much as 20% at 400°C, and by as much as 95% at 900°C (Bailey 2005). This strongly suggests that management of UCG operations to achieve production borehole temperatures less than 400°C is highly desirable. In tandem with softening of steel casings is the likelihood of significant thermal expansion, which, *in extremis*, could lead to extension of the casing in the longitudinal direction. Extension of casing is likely to result in a reduction in the bond between the outer surface of the casing and the adjacent grout, potentially compromising the integrity of the annular seal, which is usually regarded as a crucial borehole safety feature in conventional gas field engineering. With regard to borehole grouts based on ordinary Portland cement, the most relevant existing literature relates to the response of concrete structures to fires. However, in fires, open faces of concrete are available to spall and crack without physical constraint. This does not provide a very good analogue for the likely behaviour of cement-based grout packed tightly between casing and rock. Some experimental data collected by the radioactive waste management industry give indications of the likely challenges. For instance, Noumowé et al. (2003) found that heating of ordinary concrete up to 110°C results in very little decrease in mechanical strength. This suggests that standard design procedures are adequate for UCG injection boreholes. Further heating of concrete, up to 310°C, decreased mechanical strength up to 35%, and increased porosity by 12–15%. At temperatures above about 200°C, moisture loss becomes significant and hydrated solids degrade, which significantly changes the microstructure of the concrete. Given the scope for differential heating of the steel casing and the grout, brittle tensile failure of grouts

Table 2 Checklist of key hydrogeological issues, and actions required for dealing with them, for all of the main phases of the life-cycle of UCG(-CCS) operations

Phase of life cycle	Key hydrogeological issues	Action required
1. Exploration and development of overall project plan	Identification of potentially sensitive surface water features and potable water aquifers	Assembly and scrutiny of geological and geophysical data, including development of regional well inventory and production of task-specific lithofacies maps, cross-sections, fence diagrams etc. Liaise with environmental regulators and develop a generic groundwater protection plan for the UCG-CCS operations, including application of standard aquifer/source protection methodologies to ensure that all surface installations are sited to ensure any risk of accidental contamination is minimized.
	Identification and delineation of aquifer units, within and above the coal-bearing sequence, that could potentially interact with UCG operations	Identify potential aquifers (especially sandstones and limestones) from above data-sets, and add specific information on hydraulic properties and water quality, where available. For each target seam, prepare maps of isopachs of strata interval to overlying aquifer(s).
2. Detailed design for underground gasification of specific seam(s)	Borehole design to ensure UCG processes can be achieved efficiently without posing any threat to freshwater aquifers.	Taking into account the requirement for each mother-hole to be completed and cased below the base of the deepest potentially sensitive freshwater aquifer, at a diameter sufficient to accommodate multiple daughter-hole 'kick offs', devise casing and grouting designs and implementation schedules, with sufficient allowance in budget and timetable for full QA/QC of borehole integrity, using geophysical techniques
	Optimizing balance between groundwater ingress (to minimize need for active steam injection) and overwhelming inrushes, which could hinder ignition or lead to excessive water vapour entrainment in the produced syngas.	For each seam to be gasified, predict strata disturbance profiles using existing techniques (e.g. NCB 1975; Orchard 1975; Singh and Atkins 1983), including estimates of maximum tensile strain likely to be induced at the base of any of the overlying aquifers identified above. (Where multiple seams are to be gasified, develop plan for bottom-up sequencing of gasification, and take cumulative effects on tensile strain at aquifer units into account).
3. Installation of borehole infrastructure	Implement phased approach to borehole installation to eliminate any risk of contamination of shallow (freshwater) aquifers	Specification of drilling for tender documents; assessment of tenders, paying special attention to method statements relating to health, safety and environmental protection. Supervision of drilling, ensuring it is undertaken in compliance with method statements and all requirements of environmental regulators.
	Implement full geophysical testing for QA/QC purposes at the end of each stage of drilling (e.g. to installation of casing in vertical mother boreholes, then for each daughter borehole), and implementation of remedial action where necessary.	Repeated testing for casing and grout integrity, using a suite of geophysical logs, including some or all of: CCTV, caliper, SP, fluid temp. & resistivity, sonic cement bond log, density, and acoustic casing scanner. If appropriate, supplement inspection with a mechanical integrity test (MIT), i.e. pressure testing of completed borehole to assess gas-tightness; von Tryller et al. 2009. Where testing shows adequate borehole integrity, authorize continuation of operations to next phase; otherwise, take remedial action (e.g. grouting, or in extremis, borehole sealing and abandonment (cf Fuenkajorn and Daeman 1996).
4. Operation of UCG injection and production boreholes	Ensure that leakage is not occurring during operations.	Review inventory of syngas production against quantities anticipated from amount of O_2 injected (using standard fires service approaches); implement any precautionary monitoring of wells in shallow aquifers required by environmental regulators
	Ensure that operating wells are not deteriorating, which would pose a risk of future leakage or contamination	As in Phase 3: repeat geophysical and MIT testing of borehole integrity (at intervals of about 3 years for wells in use longer than that). Where integrity remains high, carry on using boreholes; otherwise take remedial action, as in Phase 3.
	Monitor progress of goafing and strata response.	Use micro-seismic, micro-gravity and other geophysical sounding techniques to monitor the formation of goaf and development of overlying zones of deformation (as in Fig. 2). Relate rates of UCG burn zone migration to deformation processes.

Table 2 continued

Phase of life cycle	Key hydrogeological issues	Action required
5. Decommission redundant boreholes	Ensure boreholes are completely sealed to prevent any long-term migration of fluids.	Use geophysical survey techniques to identify any points in casing where particular attention is needed, implement topical grouting at those points, and then complete overall sealing of boreholes in line with best practices (cf Fuenkajorn and Daeman 1996)
	Agree and implement plan for post-closure vigilance.	Considering industry experience worldwide, which suggests that even properly sealed boreholes can eventually become preferential flowpaths for leakage (Miyazaki 2009), and also taking into account proximity of sealed boreholes to any sensitive potential receptors, agree on a long-term surface monitoring strategy with regulators (establishing an endowment fund to pay for this in the long-term if appropriate), and implement it.
6. Re-using former UCG injection boreholes for CO_2 injection	Assess suitability of wells and refurbish them to suitable standard.	As in Phase 3: repeat geophysical and MIT testing of borehole integrity and refurbish as necessary.
	Implement CO_2 injection	Fit out surface infrastructure and commence injection; install/reinstate micro-seismic monitoring arrays to remotely monitor the progress of CO_2 migration into the subsurface storage zone (cf Riding and Rochelle 2009); undertake surface CO_2 surveys (if required) and monitor around all sealed, abandoned boreholes.
7. Post-injection monitoring of CO_2 storage	Agree and implement plan for post-injection monitoring.	Decommission any remaining redundant boreholes, as in Phase 7; use micro-gravity and/or electromagnetic arrays to remotely monitor the long-term retention of CO_2 in and above UCG goaf zones. Continue micro-seismic monitoring; undertake surface CO_2 surveys (if required) and monitor around all sealed, abandoned boreholes.

cannot be ruled out, at least locally. Given all of these factors, it is clear that the design and quality control of construction for UCG production boreholes needs to be pursued to far more stringent standards than is the case for injection boreholes. Modelling techniques exist which could be applied to explore the likely co-evolution of heat and moisture content in borehole grouts (e.g. Davie et al. 2006); it is proposed that these be refined and deployed to support future UCG production borehole design.

With regard to re-use of UCG boreholes in CCS operations, there must be a clear preference to re-use the former injection boreholes. Former production boreholes are likely to have suffered degradation of casing and grout, especially at deeper depths, and these could be expected to be less resistant to the corrosion anticipated from interaction with supercritical CO_2. Former production boreholes must be carefully sealed; procedures are documented in detail by Fuenkajorn and Daeman (1996).

At all stages of borehole engineering for UCG(-CCS), integrity testing of the as-built structures is recommended. For the purposes of discussion, it is convenient to introduce the terminology of 'mother' and 'daughter' holes: a mother hole is an initial (generally vertical) borehole of sufficiently large diameter to accommodate future directional drilling of daughter holes from points within it. Daughter holes are the (generally smaller diameter) subsidiary boreholes drilled directionally from points within mother holes. It is recommended that geophysical testing of borehole integrity be implemented at the following stages of operation:

- On completion of each vertical mother hole to a depth below the deepest potentially vulnerable aquifer, at which point the largest diameter permanent casing will be grouted in place;
- On completion of each daughter borehole, especially where these are partially cased;
- On completion of UCG injection/production service, or at intervals of not more than 3 years for wells in continuing use (3 years being a period long enough for any incipient corrosion of casing to become detectable), and;
- Before re-use for CCS.

If any problems are identified at any of these stages, remedial work can be undertaken before proceeding.

The following suite of downhole sondes, used in combination, provides established technology for comprehensive testing of casing and grout integrity:

- Dual CCTV—for direct visual identification of any corrosion or mechanical damage of casing
- Caliper—to detect any variations in casing diameter, which might occur where corrosion opens up holes in the casing wall
- Spontaneous potential—to detect electrical potentials arising from localised electrochemical differences

between any water in the borehole and the borehole wall, which might indicate loci of active corrosion
- Fluid temperature—to help identify discrete leaks on the casing wall, where sealing off of groundwater may have been compromised
- Fluid resistivity—to corroborate the existence of inflows through breached casing
- Sonic bond—to directly measure the presence and thickness of grout between the casing and the rock
- Density—to reveal any abrupt changes in casing materials (e.g. those due to oxidative corrosion which could produce an efflorescent rust which would be of lower density than mild steel etc.)
- Acoustic casing scanner (acoustic televiewer)—this will show any breaches of the casing, even in water too turbid for direct CCTV observation to work.

Pressure testing of completed wells can also be conducted prior to commissioning them for use in developing long term CO_2 stores, using the mechanical integrity test (MIT) technique originally developed for underground storage of hydrogen in salt caverns, which has recently been expanded in scope by the inclusion of ultrasonic geophysical tests to accurately determine the interface between injected fluid and native groundwater (von Tryller et al. 2009). Provided the MIT test shows the borehole casing and grout are sufficiently gas-tight, CCS could proceed, with the focus of attention then turning to long-term monitoring of long-term retention of injected CO_2 in the subsurface. A dilemma arises at this point, for the usual hydrogeological instinct to install monitoring wells would inherently increase the risk of CO_2 leakage to surface. For this reason, remote geophysical monitoring approaches are preferred, and these have been deployed at full-scale for real CCS projects, both on-shore (e.g. Weyburn, Saskatchewan; Riding and Rochelle 2009) and offshore (Sleipner, Norwegian North Sea; Chadwick et al. 2009). Micro-seismic, micro-gravity, and electromagnetic monitoring techniques appear to be amongst the most promising approaches (Chadwick et al. 2009), which (at least in onshore settings) can be backed up with surface monitoring of CO_2 (Riding and Rochelle 2009).

In the event that leakage is detected, mitigation options are likely to include re-grouting of any leaking wells, which could vary from repair to complete sealing and abandonment (Fuenkajorn and Daeman 1996). If all else fails, CO_2 can be extracted and transferred elsewhere.

Summary and Conclusions

This paper has considered hydrogeological issues relevant to UCG operations (Fig. 1), and the subsequent use of voids formed by UCG (Fig. 2) and overlying strata subject to deformation as those voids collapse (Fig. 4), as sites for storing CO_2 separated from the syngas. Criteria for managing potential groundwater ingress and/or trapping of injected CO_2 have been developed by application of analysis techniques originally developed to simulate the response of strata to longwall mining (Figs. 2 and 3). Of particular importance is the development of a 'pressure arch' above the gasification zone, which can serve as a low permeability barrier between that zone and the ground surface. Table 2 summarizes the key hydrogeological issues requiring investigation and decision-making at the various stages in the life cycle of a UCG or UCG-CCS operation. It is recommended that Table 2 be used as an *aide memoire* by hydrogeological advisors during the development of UCG(-CCS) projects in the field.

It is clear that UCG (with or without subsequent CCS in the same voids) cannot be regarded as a panacea. Although UCG has the advantage over conventional deep mining that it does not involve human entry to the subsurface environment, this same fact means that direct process observation is not possible. There still exists a significant deficit of direct experience and published advice on long-reach directional drilling in coal (cf Fig. 1), and there is no substitute for experience: only sustained UCG activity will yield the mature process understanding needed to ensure, for instance, that suites of boreholes are operating at sufficient scale and efficiency to smooth out the inevitable peaks and troughs in total syngas production as contributions from individual boreholes wax and wane. There is no a priori reason to assume that the future UCG industry will be any less technically demanding than longwall mining. Similarly, it will only be with sustained geophysical and hydrogeological monitoring, and thermo-hydro-mechanical modelling, building on the pioneering work of Advani et al. (1986) and others, that the models used in this paper to predict tensile strains and aquifer responses (which are borrowed from longwall mining) will be replaced with updated models that take full account of the differences between UCG and longwall operations, both in terms of ultimate geometry and time-scales of goafing. If UCG(-CCS) is indeed to be the bridge to a renewable future, it will be essential that the skills and experience of the mine water management community are maintained and honed to meet the needs of this new industry.

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in the Subsidence Engineers' Handbook (NCB 1975), which I used to develop the model results shown in Fig. 3.

References

Advani SH, Lee JK, Min OK, Chen SM, Tseng YP (1986) Coupled thermo-mechanical and poro-mechanical response evaluations associated with underground coal conversion. US Department of Energy Report DOE/LC/10886-2048, Washington

Bailey C (2005) One-stop shop in structural fire engineering. http://www.mace.manchester.ac.uk/project/research/structures/strucfire/default.htm. Accessed 11 Dec 2010

Bičer N (1987) The inflow of water into mine workings. PhD Thesis, Department of Mining Engineering, Newcastle University, Newcastle

Booth CJ (2002) The effects of longwall mining on overlying aquifers. In: Younger PL, Robins NS (eds) Mine water hydrogeology and geochemistry, Special Publication vol 198, pp 17–45. Geological Soc., London

Boysen, JE, Covell JR, Sullivan S (1990) Rocky Mountain 1 Underground Coal Gasification Test, Hanna, Wyoming, results from venting, flooding and cooling of the Rocky Mountain 1 UCG cavities. Research report, US Department of Energy contract # DE-FG21-88MC25038, Western Research Inst, Laramie

Brady BHG, Brown ET (1993) Rock mechanics for underground mining, 2nd edn. Chapman and Hall, New York City

Burton, E, Friedmann J, Upadhye R (2006) Best practices in underground coal gasification. US Department of Energy Research report, contract # W-7405-Eng-48, Lawrence Livermore National Laboratory, CA

Buscheck TA, Sun Y, Hao H, Wolery TJ, Bourcier W, Tompson AFB, Jones ED, Friedmann SJ, Aines RD (2010) Combining brine extraction, desalination, and residual-brine reinjection with CO_2 storage in saline formations: implications for pressure management, capacity, and risk mitigation. In: Proceeding, 10th international conference on greenhouse gas control technologies, RAI, Amsterdam

Chadwick RA, Arts R, Bentham M, Eiken O, Holloway S, Kirby GA, Pearce JM, Williamson JP, Zweigel P (2009) Review of monitoring issues and technologies associated with the long-term underground storage of carbon dioxide. In: Evans DJ, Chadwick RA (eds) Underground gas storage: worldwide experiences and future development in the UK and Europe, Special Publication vol 313, pp 257–275. Geological Soc, London

Couch GR (2009) Underground coal gasification. IEA Clean Coal Centre. International Energy Agency, London

Davie CT, Pearce CJ, Bicanic N (2006) Coupled heat and moisture transport in concrete at elevated temperatures—effects of capillary pressure and adsorbed water. Numer Heat Trans A-Appl 49:733–763

Dumpleton S (2002) Effects of longwall mining in the Selby Coalfield on the piezometry and aquifer properties of the overlying Sherwood Sandstone. In: Younger PL, Robins NS (eds) Mine water hydrogeology and geochemistry, Special Publication vol 198, pp 75–88. Geological Soc., London

Evans DJ, Chadwick, RA (eds) (2009) Underground Gas Storage: Worldwide Experiences and Future Development in the UK and Europe, Special Publication vol 313. Geological Soc, London

Fuenkajorn K, Daeman JJK (eds) (1996) Sealing of boreholes and underground excavations in rock. Chapman and Hall, London

IPCC (2005) IPCC special report on carbon dioxide capture and storage. In: Metz B, Davidson O, de Coninck HC, Loos M, Meyer LA (eds) Prepared by working group III of the intergovernmental panel on climate change. Cambridge Univ Press, Cambridge

Liu S, Li J-G, Mei M, Dong D-L (2007) Ground water pollution from underground coal gasification. J China Univ Min Technol 17(4):467–472

McCracken R (2008) Mining without mines: UCG. Energ Econ 31: 216

Miyazaki B (2009) Well integrity: an overlooked source of risk and liability for underground natural gas storage. In: Evans DJ, Chadwick RA (eds) Underground gas storage: worldwide experiences and future development in the UK and Europe, Special Publication vol 313, pp 163–172. Geological Soc, London

Moran CJ, Cuff C, da Costa J (2011) Summary of considerations and recommendations on the environmental evaluations of Cougar Energy. Report, independent scientific panel on underground coal gasification to the department of employment, economic development and innovation. http://www.derm.qld.gov.au/environmental_management/ucg/documents/cougar-energy-report.pdf. Last accessed 21 Feb 2011

NCB (1975) The subsidence engineers' handbook. National Coal Board Mining Department, London

Noumowé A, Ranc G, Hochet C (2003) Moisture migration and thermo-mechanical behaviour of concrete at high temperature up to 310°C. Trans, 17th international conference on structural mechanics in reactor technology, Prague, Czech Republic, Paper # H01-3. http://www.iasmirt.org/SMiRT17/H01-3.pdf. Last accessed 11 Dec 2010

Oliver RL (1987) Results from the controlled excavation of the TONO 1 UCG cavity, Centralia, Washington. In: Proceedings, 13th annual underground coal gasification symposium, Laramie, US Department of Energy Report DOE/METC-88/6095, pp 371–381

Orchard RJ (1975) Working under bodies of water. The Min Eng 170:261–270

Riding JB, Rochelle CA (2009) Subsurface characterization and geological monitoring of the CO_2 injection operation at Weyburn, Saskatchewan. In: Evans DJ, Chadwick RA (eds) Underground gas storage: worldwide experiences and future development in the UK and Europe, Special Publication vol 313, pp 227–256. Geological Soc, London

Robinson R (2000) Mine gas hazards in the surface environment. T I Min Metall A 109:A228–A236

Roddy DJ, Younger PL (2010) Underground coal gasification with CCS: a pathway to decarbonising industry. Energ Environ Sci 3:400–407

Shafirovich E, Varma A (2009) Underground coal gasification: a brief review of current status. Ind Eng Chem Res 48:7865–7875

Shoup R, Lips JP (2010) Subterranean navigation. Ingenia 45:31–35

Singh RN (1986) Mine water inundations. Int J Mine Water 5(2):1–28

Singh RN, Atkins AS (1983) Design considerations for mine workings under accumulations of water. Int J Mine Water 4:35–56

Stracher GB, Taylor TP, Prakash A (2002) Coal fires: a synopsis of their origin, remote sensing detection and thermodynamics of sublimation. In: Shaw S, Fortin S (eds), Environmental technology for mining: case histories of mine reclamation and regulation. Robertson Geo-Consultants Inc, Reno, Nevada, pp 1–8. http://technology.infomine.com/enviromine/case_hist/coal%20fires/Stracher_et_al.html. Last accessed 11 Dec 2010

Strahan D (2007) The last oil shock: a survival guide to the imminent extinction of petroleum man. John Murray Ltd, London

Trainer T (2006) Renewable energy cannot sustain a consumer society. Springer, Heidelberg von Tryller H, Reitze A, Crotogino F (2009) New procedure for tightness tests (MIT) of salt cavern storage wells: continuous high-accuracy determination of relevant parameter, without the need to use radioactive tools. In: Evans DJ, Chadwick RA (eds) Underground gas storage: worldwide experiences and future development in the UK and Europe, Special Publication vol 313, pp 129–137. Geological Soc, London

Younger PL (1992) The hydrogeological use of thin sections: inexpensive estimates of groundwater flow and transport parameters. Q J Eng Geol Hydroge 25:159–164

Younger PL, Adams R (1999) Predicting mine water rebound. Environment agency R&D technical report W179, Bristol

Younger PL, Sapsford DJ (2004) Evaluating the potential impact of opencast coal mining on water quality (Groundwater Regulations 1998). An assessment framework for Scotland, prepared for the Scottish Environment Protection Agency (SEPA). Newcastle Univ/NuWater Ltd, Newcastle Upon Tyne

Younger PL, Banwart SA, Hedin RS (2002) Mine water: hydrology, pollution. Remediation. Kluwer Academic Publication, Dordrecht

Younger PL, Gluyas J, Cox M, Roddy DJ (2010a) Underground coal gasification. Ingenia 43:42–46

Younger PL, González G, Amezaga JM (2010b) Water management issues in the underground gasification of coal and the subsequent use of the voids for long-term carbon dioxide storage. In: Wolkersdorfer C, Freund A (eds) Mine water and innovative thinking. Proceedings, international mine water assoc symposium, Cape Breton University Press, Sydney, pp 67–70

Younger PL, Roddy DJ, González G (2011) King coal: restoring the monarchy by underground coal gasification coupled to CCS. In: Vining BA, Pickering SC (eds) Petroleum geology: from mature basins to new frontiers, Geological Soc, London. Proceedings, 7th petroleum geology conference, vol 2, pp 1155–1163