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# Recent Development on Underground Coal Gasification and Subsequent $CO_2$ Storage

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**Abstract**

Underground coal gasification (UCG) is the in-situ conversion of deep underground coal to synthesis gas for heating, chemical manufacturing and power generation. UCG has been the subject of extensive pilot testing but technical and environmental concerns remain, not least its greenhouse gas emissions. An attractive solution is to combine UCG with $CO_2$ capture and storage (CCS) so that the $CO_2$ generated from the UCG and combustion of synthesis gas is re-injected back underground in the UCG cavities, adjacent unmineable coal seams and stressed strata. Thereby the emissions from UCG are eliminated and deep coal reserves become a new source of energy supply. This paper reviews the recent global development of UCG projects, the research progress of UCG technology and the technical developments and economic feasibility of UCG-CCS in recent EU projects.

**Keywords:** UCG; CCS; Computational modelling; Experimental tests

## 1. Introduction

Despite the ongoing trend towards renewable energy sources, fossil fuels, particularly coal, will continue to be a major source of energy for many decades – a 20% increase in coal demand is predicted between 2008 and 2035 (IEA, 2010). However, coal is one of the primary environmental polluters and its use is contributing to the rising $CO_2$ concentration in the atmosphere. The key to reconciling these differences lies in the application of clean coal technologies (CCTs). Furthermore, many of the world's coal reserves are too deep to exploit by conventional methods (such as surface mining or underground mining). Underground coal gasification (UCG) provides access to coal deposits that would otherwise remain unused and an attractive route to carbon capture and storage (CCS).

UCG is a technology to gasify the coal in situ in order to produce synthesis gas, which is a mixture of mainly hydrogen, carbon dioxide, carbon monoxide and methane. It involves a minimum of two wells (injection well and production well) partly drilled into the deep coal seam some distance apart, and connected by a channel through which gases can flow, as shown in Figure 1. During the UCG process, the gasifying agent (air, or oxygen, and possibly added steam) is supplied via the injection well to the underground gasification chamber, and the product gases are extracted via the production well to the surface for treatment and use. This process develops cavities within the coal seam and the roof may collapse, resulting in further growth of the cavity voids. Once the quality of the product gas has declined in the reaction zone, new coal is then exposed by moving the injection point and the process continues until the length of the borehole is exhausted. The size of the cavity formed during UCG has direct impacts on the economic and environmental aspects of a UCG project. Commercial-scale UCG operations would involve multiple boreholes/wells to produce sufficient quantities of syngas. UCG offers the potential for using the energy stored in coal in an economic and

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environmentally sensitive way, particularly from deep deposits which are unmineable by conventional methods. It is rapidly becoming a viable commercial activity in Australia, South Africa and China, while many Eastern European countries are intensively working for its commercialization (e.g. Poland and Hungary). If UCG were to be successfully developed and widely deployed, then the world's coal reserves are likely to be revised upwards by a substantial amount.

Although trial operations of UCG began in the 1930's (Zamzow, 2010), the capture and storage of $CO_2$ as an integral part of the operation has only been considered in recent years. UCG-CCS entails injecting and storing the $CO_2$ produced in the underground gasification process and as a by-product of the shift reaction in which the CO in the extracted synthetic gas is reacted with steam to produce hydrogen and $CO_2$. In addition to the injection of the separated $CO_2$ into adjacent coal seams, the UCG cavities, boreholes and created fractures could provide an additional capacity for $CO_2$ storage (Pei et al., 2010). Both UCG and CCS technologies have been tested separately and to some extent already applied commercially, but no site test has yet combined those two technologies. A few deep trial UCG projects have been undertaken (e.g. Swan Hills, Canada) and are useful for identifying and evaluating technical issues when implementing UCG-CCS projects.

This paper reviews the recent practicalities of worldwide UCG projects and the research activities that are associated with UCG technologies, with an emphasis on the developments during the last five years. The recent development on computational modelling as well as experimental (both laboratory and field scale) tests of UCG process are highlighted. Base on the research outcomes from a previous UCG-CCS project, the technical challenges and economic feasibility of combining UCG with $CO_2$ storage are also discussed.

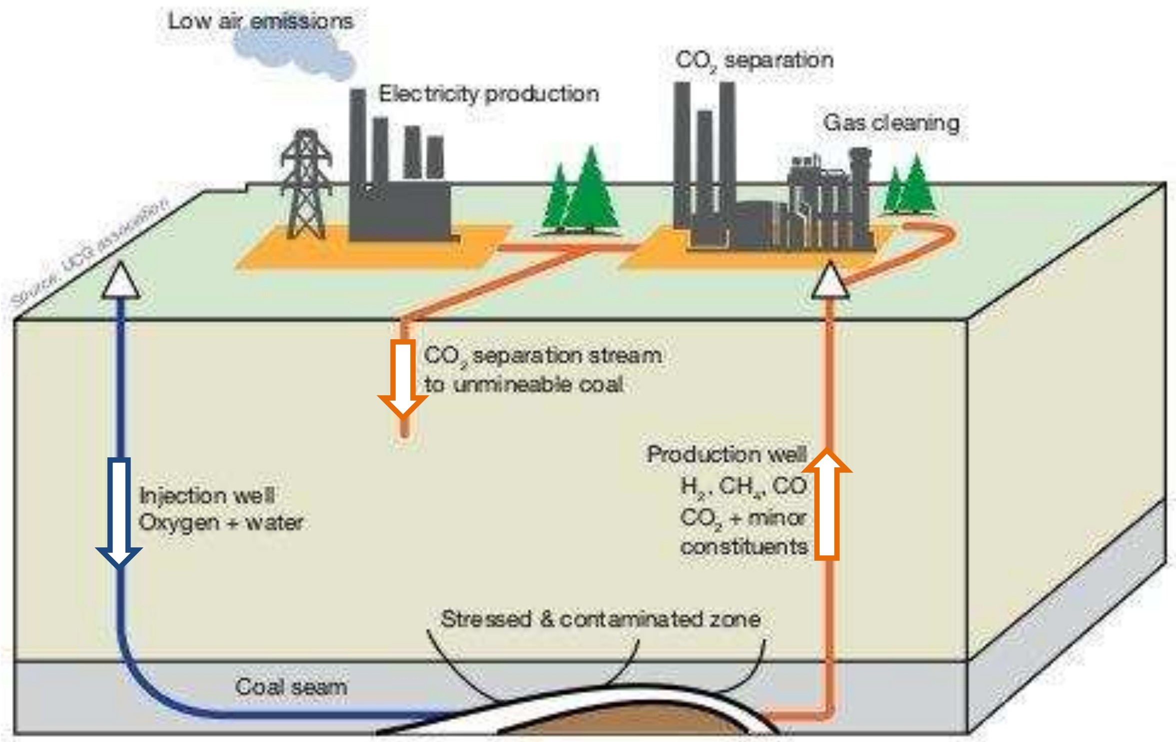



Figure 1 Schematic diagram of UCG process (Source: UCG association)

## 2. Recent practicalities of UCG projects

UCG involves multi-physics/chemistry processes which take place at different time and length scales, and requires sophisticated modelling supported by full-scale tests to advance the technology. Although large scale UCG projects have been developed in the past, *e.g.* Angren, Uzbekistan, and commercial projects are currently underway in many countries, financial institutions, investors and sometimes government sectors, need a greater understanding of the technical, economic and environmental risks of UCG in order to permit or finance the commercial projects. The development work currently under way is aiming at converting the knowledge gained into commercial practice and it is increasingly recognized that sharing experience and skills will significantly increase the economically viability of UCG. This section reviews current UCG developments and the potentials for the exploration of coal deposits at the global scale in terms of its implementation across the various continents over the past 5 to 10 years. Figure 2 is a snapshot of some of the UCG activities, which will be described in detail in the following sections.

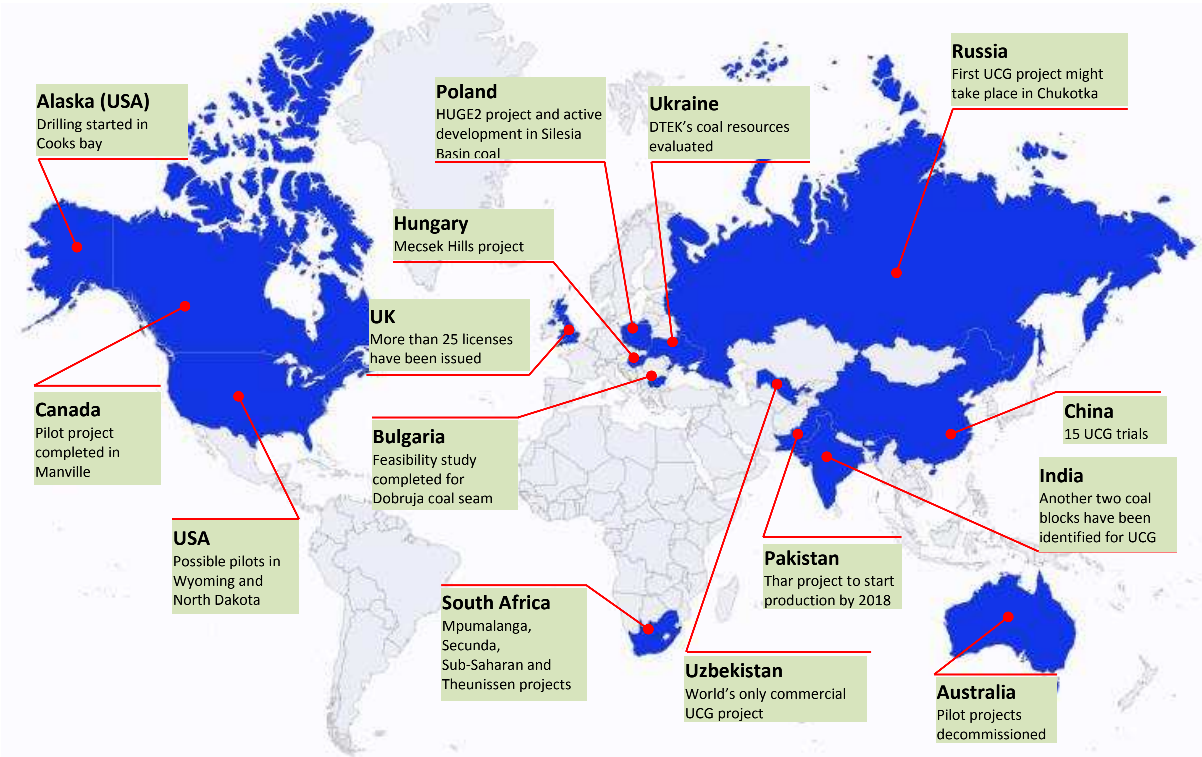



Figure 2 Worldwide underground coal gasification: a snapshot (Yang *et al.*, 2014).

### 2.1 Australia

Substantial progress and employment of the UCG technology has been demonstrated in Australia, where development took a lead between 2000 and 2012. The work was initiated by the private company, Linc Energy which built a demonstration plant for UCG at Chinchilla, Queensland in 1999. A total of five UCG reactors were tested, and the work was accompanied by the construction of a gas to liquid pilot plant for diesel fuel (Linc Energy, 2013). Another company, Carbon Energy Ltd, has constructed two reactors, and used the syngas produced in a demonstration 1MW power generation unit for a short time. Although other companies such as Cougar Ltd have attempted to pursue their own UCG projects, this has been stopped as a result of an assessment of the impact on the environment and other factors. UCG in Australia has now been affected by the reaction to the Cougar problems at Kingaroy and the Queensland Government has published an independent scientific report on UCG, which requires each company to demonstrate decommissioning before further activities are permitted. Australia has shown willingness to undertake CCS projects involving power generation (*e.g.* the CarbonNet project in Victoria) and has shown interest in forming partnerships with European research institutions on UCG-CCS.

**2.2 Asia**

UCG activities in Asia have been progressive. The proven coal reserve in **China** is 114.5 BT and because of the limitations in manual mining, about 50 % of China's coal resources are unmined. China's interest in UCG is provoked by the government's commitment to ensure a reduction in pollution from coal-fired power plants. China has run about 15 UCG trials to date, aided by the UCG Research Center of China University of Mining and Technology (Beijing) (CUMTB) which has carried out theoretical research, UCG model tests and series of field tests. CUMTB, in collaboration with the coal industry, has brought forward the development of UCG in China. The maturing of UCG is of great importance to China and the country is trying to stimulate and enhance cooperation with other countries and foreign companies that have interest in accelerating the development and application of the UCG technology. ENN Group, which is part of the Hebei based XinAo Group and one of China's largest private gas companies with large overseas interests, is working closely not only with CUMTB but internationally with higher-learning institutes and corporations in Uzbekistan, USA, Australia, South Africa and EU. In 2011, a $1.5 billion commercial partnership was launched between Seamwell International Ltd (UK) and Chinese Energy Conservation and Environmental Protection Group (CECEP, China) to gasify 6 million tons of buried coal per year in Inner Mongolia's Yi He coal field, aiming to generate 1,000 MW of power for 25 years. Australian based Carbon Energy's commercial UCG project is located at Haoqin Coal Field in Xiwuqi in Inner Mongolia, China. It is a technology license agreement (TLA) with Zhengzhou Coal Industry Group Co Ltd (Zhengzhou Group) to be the exclusive underground coal gasification (UCG) technology partner for the project in China (Carbon Energy Ltd, 2013).

In 2005 the Neyveli Lignite Corporation in **India** initiated a new project, funded by the Ministry of Coal to select a suitable lignite block for UCG trial, carry out pilot-scale studies and assess the heat value of the gas produced. Subsequently, the Central Mine Planning & Design Institute Limited (CMPDI) prepared data packages for five prospective UCG sites and appointed Skochinsky Institute of Mining (SIM), Russia as consultants. One of the five sites, the Kasta block in Raniganj coalfield was selected for a UCG pilot and borehole drilling is completed. Another two coal blocks, Kaitha Block of Central Coalfields Ltd and Thesgora "C" Block of Western Coalfields Ltd were identified by Coal India Limited (CIL) in July 2014 for commercial development.

In December 2009 the Thar Coal and Energy Board (TCEB) in **Pakistan** established a joint public private partnership with world renowned companies from China, Germany and South Africa to study the geological, hydrological, cultural and environmental impact of Thar Coal Mining with a view to mining 6.5MT/y of coal and generating 1,200 MW of electric power. In 2010 a UCG project was started in Block V of Thar Coal deposits (containing 1.4 billion tons of low-grade lignite coal reserves) (Khurshid, 2011). The aim was to set up two pilot 5MW power plants and to generate 8,000 MW from Thar Coal by 2015. During the construction phase of the UCG pilot, problems were encountered mainly concerning hole linkage, water incursion, aquifer characterisation and ignition of coal. The plant now is expected to produce electricity by 2018 (Tribune, 2015).

**2.3 North America**

In North America the USA and Canada have conducted field trials and modelling work on UCG for decades in both industry and research establishments. The **USA** was the principal driver of UCG throughout the 1980's and early 1990's but work virtually stopped in the mid 1990's when natural gas prices fell to record low levels. A revival of interest in UCG occurred about 10 years later (2005), mainly by Lawrence Livermore National Laboratories (LLNL) who secured funding from US Department of Energy (DOE) to undertake a review of Best Practice in UCG in 2006 (Burton et al., 2007). LLNL have continued research in UCG with the emphasis on developing an integrated 3D full simulator of the cavity growth (reaction, geo-thermal, hydrology & fluid mechanics) (Nitao et al., 2011).

The commercial development of UCG in the US has been undertaken by mainly Australian and Canadian Companies (Linc Energy, Carbon Energy and Ergo Energy and Laurus). Linc Energy has acquired a project in Wyoming to develop UCG and GTL (Gas To Liquids) from UCG. An application to the Environmental Protection Agency (EPA) and the Wyoming Department of Environmental Quality for a pilot study has been approved in September 2014. Linc Energy also has another potential UCG project in Cooks bay Alaska in association with the State Authorities, which has just started exploratory drilling in September 2014. Carbon Energy also has coal assets in Wyoming and North Dakota for a possible future pilot (Carbon Energy Ltd, 2012). The Canadian Company Laurus Energy has plans to develop a UCG project at Stone Horn Ridge near the Beluga River in southern Alaska in conjunction with CIRI (Cook Inlet Region Incorporated, a native American-owned corporation in Alaska). The project will be designed and developed with the capability for CCS

Currently, the most advanced Canadian UCG development is a pilot project completed by Swan Hills Synfuels with support from the Alberta Energy Research Institute (AERI). It was set in the Manville coal seams between 4 to 5.2 metres thick at a depth of 1400 m, the deepest UCG ever conducted in the world. The trial gasification has used a single pair of wells to produce gas with a CV of $10MJ/m^3$. The Government of Alberta and Swan Hills Synfuels agreed funding for $285 million to cover the CCS part of the project, but this has since been withdrawn. Laurus Energy Canada Inc. is a licensee of the Ergo Exergy's proprietary UCG technology and is seeking projects in North America to demonstrate that large quantity of syngas can become an important feedstock to power generation, chemical and fertilizer plants in the Region. Although permits for its project in Alberta were received in February 2011, it was delayed by the fall in natural gas prices in North America due mainly to shale gas. Other organisations such as Sherrit Technologies and University of Calgary are involved in the development of clean energy technologies and performing feasibility studies and Ergo Exergy are technology supplies to a number of projects worldwide, including South Africa, New Zealand and Alaska (Ergo Exergy, 2014).

### 2.4 South Africa

The energy company Eskom is the first to initiate the investigation of UCG in **South Africa** (Eskom, 2013). In 2007 Eskom commissioned a UCG Pilot Plant with a capacity of about 3MW next to Majuba Power Station in Mpumalanga and in 2010 the syngas produced was used for co-firing with coal in the power station. The Majuba coal deposit is bituminous coal with thickness range of 1.8 m to 4.5 m and lies at depth between 250 m and 380 m. Sasoil Limited has been investigating UCG for their gas-to-liquid (GTL) process in Secunda and has snow joined forces with Eskom in a 1B Rand project to jointly develop commercial UCG in South Africa. Other projects in Africa include the sub-Saharan project with Linc Energy and Exxaro Resources, and the Theunissen project with Africary Holdings Ltd (Green, 2014).

**2.5 Europe**

UCG has a long theoretical and field-based history in the UK, France, and the Former Soviet Union (FSU) (Shafirovich and Varma, 2009). The activities have been carried out for more than 50 years in the FSU and later in Russia itself. Scientific and engineering knowledge on UCG have been continuously developed, and has led to several UCG operations. Since 1996, when field work stopped, Russia has been improving the basic structural components and operational parameters of UCG technology. The new designs and technological know-how that have recently emerged are protected by a series of Russian patents. It is anticipated that Russia's first UCG project will take place soon in Chukotka where Clean Energy, a subsidiary of Linc Energy, investigated the coal deposit there in 2013 and concluded at least two sites are suitable for the implementation of UCG (The Moscow Times, 2013).

**Ukraine** has continued to work on UCG after independence from FSU. The country participated in the first RFCS funded HUGE Project (2007-2010) by providing an extensive review of the Soviet work on UCG and contributed to the design of the underground gasifier design at the Barbra Mine, Katowice. The Ukrainian Technological Academy (UTA) has patented a geo-technology process for obtaining hydrogen by purifying synthesis gas from UCG (UAHE, 2010), and in December 2012, Linc Energy and the Ukrainian company DTEK holdings started to evaluate UCG potential of DTEK's coal resources (Linc Energy, 2012) but this is now on hold.

A company which has been active in UCG in **Hungary** is Wildhorse Energy, which is focussed on implementing UCG and developing its prospective uranium deposit in the Mecsek Hills in the Pécs region of Southern Hungary. In July 2012 the Hungarian Government approved UCG as a technology and planed for the construction of a 130 MW pilot plant to demonstrate the ability of UCG dependent on seeking investment partners.

The **Polish** Government views UCG as a method to exploit its large coal reserves for power generation. Small-scale UCG experiments were carried out in the 1960s and 1970s and since 2007 Poland has begun to re-evaluate its UCG activities through new exploratory and field tests in the country. An important EU project undertaken by Central Mining Institute (GIG in Polish) is the Hydrogen Oriented Underground Coal Gasification for Europe project (HUGE, 2007-2010), funded under the Research Fund for Coal and Steel (RFCS) programme and bringing together eleven partners from seven countries. Its main focus was the theoretical and experimental development of in-situ production of hydrogen-rich gas from coal using underground gasification. A follow-up project HUGE2 (2011-2014), which is also financed by RFCS, focuses on the environmental and safety aspects associated to the UCG process, including underground water contamination, potential leakage of toxic gases. Poland also has a nationally funded UCG project, which is being constructed in an active coal mine in Upper Silesian Basin, to produce an industrial plant design by 2015. In addition, Linc Energy has a joint venture to develop UCG in Poland with an exploration site licence in Silesia (Green, 2014).

A comprehensive feasibility study has been completed for developing UCG in Dobruja coal deposit in **Bulgaria** under a project funded by RFCS (Sheng et al., in press). Geological model, geo-mechanical and cavity models and hydro-geological model have been developed for the target area. In addition, engineering, drilling and completion requirements of wells were investigated and the environmental and economic assessment of the combination of UCG and subsequent $CO_2$ storage has been performed.

UCG development in the **UK** goes back to the 1950's field trials and a new initiative on UCG (2000-2005) led by the UK Coal Authority and supported by the UK Department of Trade and Industry (DTI) investigated the feasibility of UCG in the UK. The main conclusion was that UCG should be seen primarily as a near-shore and estuary technology and a site was identified in the Firth of Forth for a possible field trial. More than 25 licences have since been issued for UCG exploration in offshore locations. The current key players are Thornton Energy (Firth of Forth), Five Quarter (Newcastle,) and Cluff Natural Resources with eight offshore sites in Firth of Forth, Liverpool, Cumbria and Durham. The geological evaluation of these license areas is all funded by key private sector investors, and planning applications are currently in preparation. In addition, the relevant energy and environmental authorities of Scotland, Wales and England are considering the permitting implications.

The review has shown that UCG is evolving as a strategic technology of growing interest worldwide for large-scale syngas production to unlock the potential of huge unminable deep coal resources with distinct cost and environmental advantages. Although much is known about the control, site selection and operation of UCG, further knowledge from modelling and field tests must be pursued to ensure that environmental impacts of full commercial deployment are fully understood and assessed. This would place coal in a sustainable, secure and competitive energy mix and allow its continued contribution to a competitive and secure energy supply. A comprehensive set of data of UCG trial projects including coal types and seam thickness has been reported in 2007 (Khads et al., 2007) but more detailed information of recent UCG projects over the past few years still needs to be updated. Key to the commercialisation and growth of the UCG industry is the collaboration and sharing of expertise and knowledge between projects and governments with experience in UCG, particularly in the area of environmental impact, planning and regulation.

EU-funded projects are one of such opportunities that set the basis for collaboration between EU countries in the field of clean coal technologies like UCG and $CO_2$ storage solutions. The countries with the greatest interest and most active R&D programs in UCG are China, India, South Africa, United States, Canada, Australian and certain Member States of the EU. China, South Africa and the US are the countries probably closest to commercialisation outside of the EU. Within the EU the countries showing the most progress are Poland, Hungary and the UK. CCS research and development is active and demonstration scale projects of both capture and $CO_2$ storage are underway in most countries, and the mature of CCS is of significant importance to facilitate the combination of UCG and CCS. Case studies of UCG-CCS have been carried out in the Powder river basin of Wyoming, USA (Zamzow, 2010) and the Williston basin, North Dakota, USA (Pei eta al., 2010). In Europe, a consortium funded by the EU has carried out a pilot investigation of in-situ hydrogen production incorporating UCG-$CO_2$ management in Poland (Zamzow, 2010).

## 3. Research development of UCG

UCG is conceptually very simple but the development of a working system has proved more difficult in practice. The main problems include accurate in-seam drilling, controlling the reaction within the seam and producing a consistent and high quality gas. Therefore trials must be undertaken at pilot scale, although they are both costly and time consuming. More research on prediction of cavity growth, site evaluations, assessment and mitigation of environmental impacts, economic studies and safety are generally required to convince financial institutions, permitting authorities and investors to support the commercial projects.

The quality of the product gas from UCG process is influenced by the coal properties as well as the operation such as feed conditions and injection points. As gasification proceeds, an underground cavity is formed. The volume of the cavity increases progressively with coal consumption and roof spalling due to thermo-mechanical fracture. As the cavity growth is irregular in three dimensions, the flow pattern inside the UCG cavity is highly non-uniform. The complexity increases further because of several other processes occurring simultaneously, such as heat transfer due to convection and radiation, spalling, water intrusion from surrounding aquifers, several chemical reactions, and other geological aspects.

Despite the fact that very few experiments have been carried out in the laboratory, there are still some lab tests reported in the past few years, with a particular purpose to understand the cavity growth as well as to validate numerical modelling. Field tests of UCG are less expensive than pilot projects but could be more useful than laboratory tests by incorporating more underground geological effects. The research from laboratory, field scale pilot test as well as advanced computational modelling of UCG are presented in this section aiming to provide an in depth overview of the recent developments.

**3.1 Laboratory and field tests of UCG**

Only a few field tests were carried out to date and limited data on cavity growth in a burning coal seam have been obtained, due to the high cost as well as the difficulty of controlling the operating variables. As a result, a number of laboratory-scale coal block gasification tests have been performed recently under a three-dimensional geometry (Daggupati et al., 2010; Liu et al., 2011; Stanczyk et al., 2011; Prabu and Jayanti, 2012). In those experiments, usually a borehole was drilled through the coal block; blast gas was injected into one end of the borehole and the product syngas extracted from the other end. However, even these tests are difficult to interpret because they are three-dimensional tests and the cavity wall temperature changes with time and along the axis of the borehole. In addition, it is difficult to apply the same or similar hydrostatic stresses on the tested coal/rock samples to represent the real UCG scenario, thus the influence of geologic condition on the cavity growth is hard to investigate at laboratory scale.

A field test was reported by Yang et al. (2008) to use two-stage gasification approach with long channel and big section for hydrogen production in Woniushan Mine, Jiangsu Province, China. In this two-stage UCG, oxygen enriched air was injected to stimulate the gasification and increase the average temperature of the coal seam up to 1000°C, and then steam is injected after the first stage of air injection to invoke the reaction between steam and the incandescence for water gas with high content of hydrogen. It is also noticed that the two-stage gasification technology is more suitable for gasifiers of large size. A similar two-stage UCG test was performed late by Liu et al. (2011) to investigate the syngas composition as well as temperature field. In the first stage, and main outcome of the test is the effect of oxygen concentration on the time duration of the two gasification stages. The temperature field during the test was measured, but it provides more information on the temperature drop along with the gasification process rather than the cavity shape.

A semi-industrial test of Enhanced-UCG (EUCG) technology was reported by Wang et al. (2009) to gasify the scattering coal seals in Zhong-Liang-Shan mine in China for three months by making use of the abandoned mine shafts as gasification channels. Due to controlled moving injection points, the operation of this specific EUCG is more controllable in terms of operational pressure and gas flow, and meanwhile it seems a feasible technology to 're-mine' the abandoned coal resources, particularly in China.

In the frame of HUGE project (Hydrogen Oriented Underground Coal Gasification for Europe), Stanczyk et al. (2011) carried out simulated UCG experiments on lignite and hard coal seams using three different gasification agents, *i.e.* air, oxygen, oxygen enriched air in an ex situ reactor. It was found that oxygen was necessary to sustain the gasification process of both lignite and hard coal. Optimal oxygen/air ratios for both types of coal were identified, although the ratio was strongly related to the reactor geometry. Later, Stanczyk et al. (2012) also adopted the two-stage gasification approach (Liu et al., 2011), used large rock and coal samples, and applied a vertical weight on the reactor to mimic the underground gasification conditions. Although the production rate of hydrogen is still the main purpose, the experiment provides invaluable information on the temperature profile for future thermodynamics analysis. Using electromagnetic technology, the horizontal projection of the cavity shape on the level of the gasification channel is also obtained, as shown in Figure 3.1.

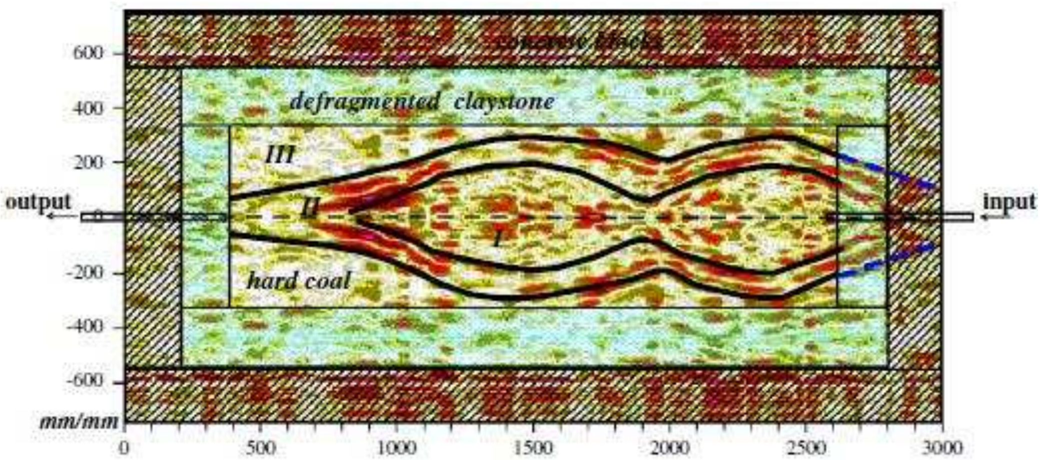



Figure 3.1 Image of horizontal projection of gasification cavities (Stanczyk et al., 2012).

The shape and rate of growth of the UCG cavity have great impact on other important phenomena, such as reactant gas flow patterns, kinetics and temperature profiles. Daggupati et al. (2010) designed a series of laboratory tests to investigate the cavity formation of lignite coal and its dependence on injection flow rate, operation time as well as the distance between injection and production wells. It was reported that the injection flow rate and operation time resulted in monotonic increases in all the dimensions of the cavity, when other factors are kept the same. Under that experimental condition, empirical correlations for cavity growth were proposed in which the correlation coefficients were obtained by fitting the experimental data using statistical software. The shape and size of the cavity in three dimensions are measured, as shown in Figure.3.2.

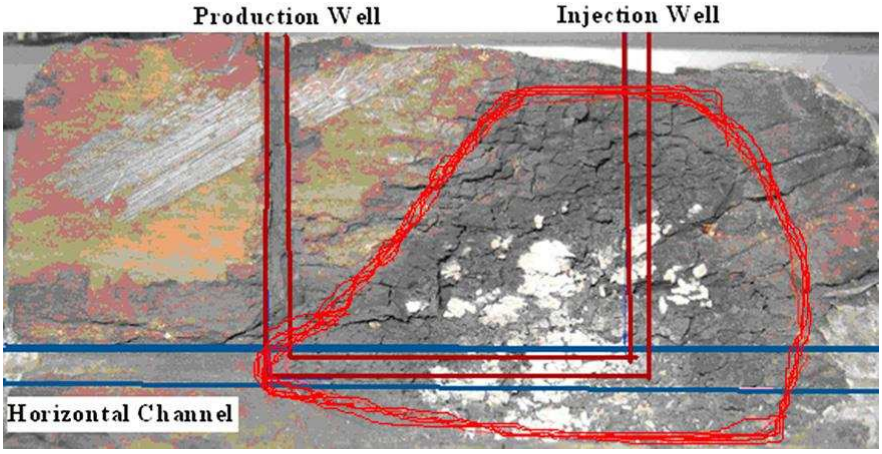



Figure 3.2 Photograph of the vertical section of the gasification cavity (Daggupati et al., 2010)

Prabu and Jayanti (2012) carried out laboratory scale studies to simulate UCG of high ash coals using pure oxygen or oxygen and steam as the gasifying agents. They investigated the effects of coal properties, and feed gas flow rate and composition on the rate of cavity growth and found that high oxygen flow rates are required to ensure the cavity expands in all directions. The high ash content (25% by weight), also produces very fine-sized ash particles which were found to fill the cavity (Figure 3.3).

Figure 3.3 Tear drop shape of cavity after gasification (Prabu and Jayanti, 2012).

### 3.2 Numerical modelling of UCG

#### 3.2.1 Modelling of cavity growth

The UCG cavity consists of coal, char, ash, rubble and voids, therefore its shape and size evolves as the gasification process proceeds. Generally the cavity size depends on the coal consumption is mainly governed by the reaction rate that takes place in the cavity reactor, whereas the cavity shape depends on the growth rates in the four directions which is influenced by the gas flow field inside the cavity, and other effects such as thermo-mechanical spalling of the coal, operating conditions and coal seam thickness. The growth as well as the final form of UCG cavity has direct influence on the economic and environmental factors of the project. Width/height ratio of the UCG cavity determines the resource recovery and the ultimate overall dimensions will dictate the hydrological and goemechanical response of the overburden. The evolution of UCG cavities and the final shape and size of the gasification channel are of vital importance for the environmental safety and geological stability of surrounding geological formation (Bhutto et al., 2013).

Efforts have been made to develop mathematic and/or numerical models, ranging from 1D, to 2D symmetric and to full 3D, to predict the UCG cavity growth. Perkins et al. (2006) developed a 1D thermo-mechanical model to investigate the effects of operating conditions (e.g., temperature, pressure, water influx, gas composition) and coal properties (e.g., thermo-mechanical spalling behaviour, reactivity, composition) on the rate of local cavity growth and the effectiveness of energy utilization (see Figure 3.4). The thermo-mechanical spalling behaviour of coal, the behaviour of the ash and the amount of fixed carbon in coal were found to most affect the cavity growth rate.

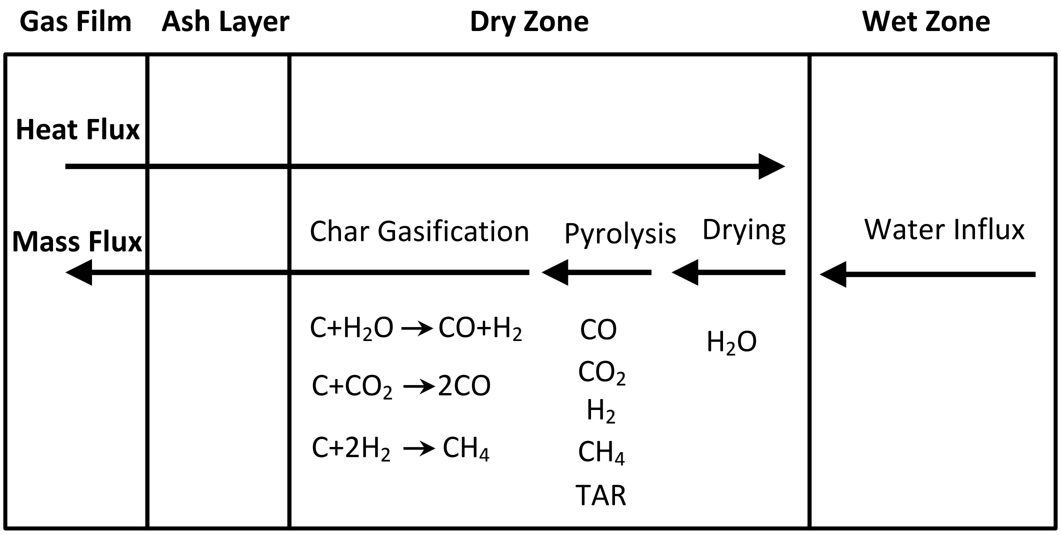



Figure 3.4 Schematic of 1D thermo-mechanical UCG model, reproduced from Perkins et al. (2006).

Chen et al. (2011) developed a 2D thermal model to calculate the temperature distribution in the vertical direction of the UCG cavity and the combustion volume by assuming a circular gasification channel. Yang et al. (2014) developed a 3D coupled thermo–mechanical finite element model to analyse the cavity growth as well as the roof deformation and ground surface subsidence. A coupled temperature–displacement procedure was adopted to simultaneously solve the stress/displacement and temperature fields. Cavity shapes and temperature profile in the coal seam during gasification were investigated by assuming the coal consumption at a specific temperature, *e.g*. the coal is assumed completely gasified once its temperature reaches 1000 degrees Celsius. It should be noted that in this thermo-mechanical modelling the cavity is represented by the elements with thermal and mechanical properties similar to syngas, but the conjunctive heat transfer through gas flow is neglected, thus the irregularity of the cavity shape cannot be accurately predicted.

To account for the chemical reaction, the UCG cavity is usually considered as either a packed bed or a free channel. Yang et al. (2004) assumed the UCG cavity as a packed bed reactor and used a set of partial differential equations to model the temperature distribution. Yang (2006) also presented a 3D unstable nonlinear numerical model of UCG to study the temperature field, concentration field as well as pressure field in the gasification panel. Khadse et al. (2006) developed a 1D transient model for UCG by viewing the UCG channel as a packed bed and the coal particles are filled in the reactor and go through the processes of oxidation and gasification in a porous space. Because there are large differences in the characteristic times of the different variables in this model, the system of equations was divided in into two parts, one consisting of steady state gas phase and energy balance in only the length domain and the other set of solid balance equations in time domain only.

The chemical processes can be coupled with the mass- and heat- transfer equations to give better prediction of temperature distributions in UCG cavity. Perkins and Sahajwalla (2007) developed a 2D axisymmetric CFD model of the UCG cavity that can be used to simulate the combined effects of heat and mass transport and chemical reaction during the gasification process. Although a number of assumptions and simplifications were made to make the simulations tractable, the results reveal the importance of transport and reaction processes occurring in the UCG cavity. Nourozieh et al. (2010) used a comprehensive porous media flow approach to construct a 3D model of UCG of thin and deep coal seam, ini whch the cavity growth is caused by char combustion and gasification reactions, and the rate of cavity growth depends on the rate of these reactions. However, other types of mechanisms such as thermo-mechanical failure, rock spalling, sidewall regression, and bulk collapse of coal are not included. Seifi et al. (2011) carried out a 3D simulation of UCG process using the STARS module of the Computer Modelling Group Software (CMG), which is a process simulator for modelling the flow of three-phase and geo-mechanical process (fracturing, compaction and rock failure), to investigate cavity shape, temperature variation, product gas composition and flow rates, taking into account heat and mass transport phenomena in conjunction with chemical reactions. Despite assuming constant thermal properties for solid components and water and also predicting the pyrolysis process with one reaction, the findings of this model are physically consistent with those in the literature in predicting syngas flow rate, cavity shape, and temperature profiles.

The actual UCG cavity is expected to be irregular in all three dimensions, and its growth rate might well be different in different directions (Daggupati et al., 2011). Furthermore, a complex non-ideal flow pattern of the reactant gas prevails in the cavity and is strongly governed by the cavity shape. In the process of UCG, the cavity shape is coherent with the gas flow. Due to buoyancy forces, the actual UCG cavity is irregular in all three dimensions, and on the other hand the cavity geometry acts as boundary for the gas flow. The characterization of the non-ideal flow patterns in UCG is an important aspect, as it is likely to significantly influence the process performance. Computational fluid dynamics (CFD) studies are essential to understand these complex flow patterns within the cavity. The phenomenological model proposed by Daggupati et al., (2011) is shown in Figure 3.5, where the focus is on the UCG cavity and flow patterns. The cavity is subdivided into discrete compartments which exchange heat and mass with the cavity roof and the non-carbonaceous rocky floor (as shown in Figure 3.6), providing significant computational savings in predictive modelling for UCG cavity flow patterns. Furthermore, the influence of injection orientation (vertical or horizontal) and radiation on the reactant gas flow has been analysed. The CFD results are further used to conduct numerical (virtual) tracer experiments and to determine the residence time distribution (RTD) or exit age distribution. Based on the flow patterns from the CFD simulations and the RTD studies, the cavity is modelled as a simplified network of ideal reactors.

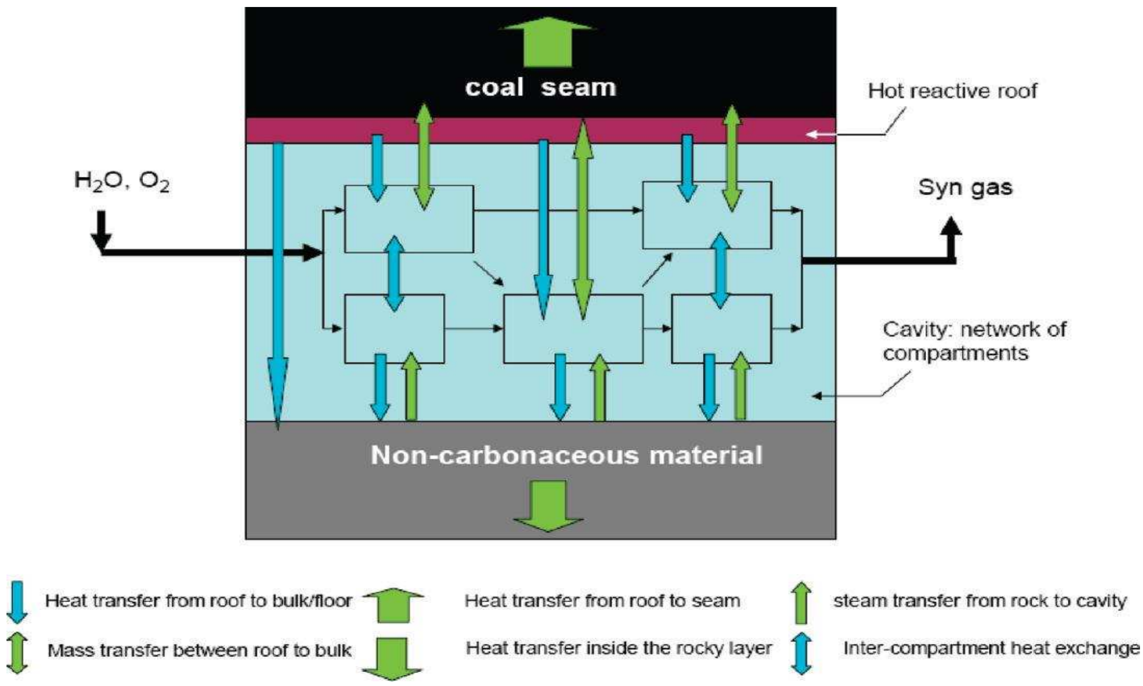



Figure 3.5 Phenomenological modelling of the underground coal gasification process

for a nonspalling case (Daggupati et al., 2011).

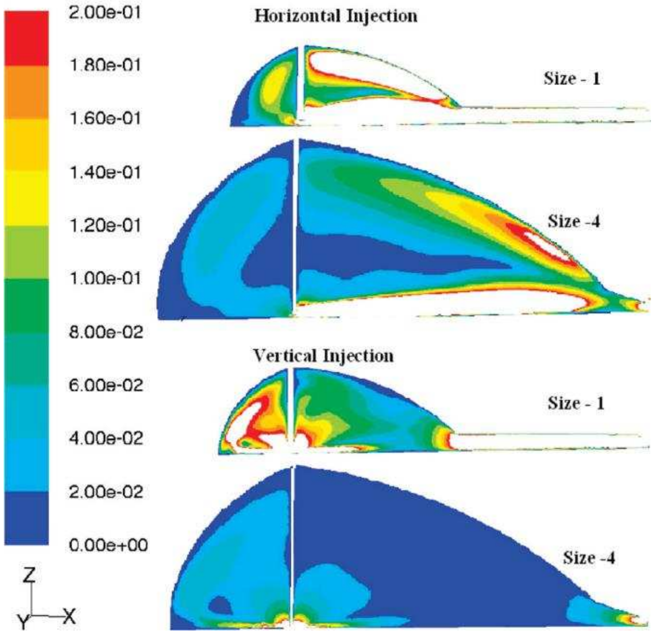
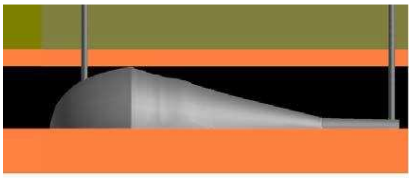
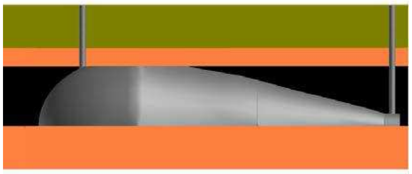



Figure 3.6 CFD Contours of the magnitude of the velocity (m/s) on a center plane (width) for different cavity sizes (Daggupati et al., 2011).

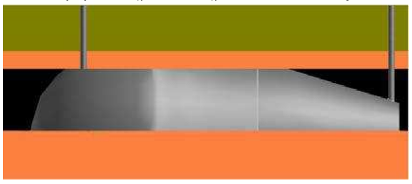
Another modelling attempt by Luo et al. (2009) has combined CFD and mathematical cavity growth model and it also showed promising results in terms of cavity shape, dimensions and coal consumption, as shown in Figure 3.7. Effects of natural and forced convection driving forces on heat and mass transfer in cavity are considered in the 2D mathematic cavity growth model which is then expanded into 3D and incorporated with CFD simulation by assuming the cavity growth is uniformly expanded towards side wall and roof wall. The information from the Chinchilla UCG trial work has been used to validate the modelling results.



(a) At 2.5 days, the cavity touched the overburden



(b) 5 days cavity size and shape



(c) 10 days cavity size and shape

Figure 3.7 Combined CFD and mathematic cavity growth model

**3.2.3 Geomechanical and Environmental modelling**

Even though UCG is operated in deep coal seams below the water table, product gas could migrate through geologic faults and openings (fractures) in rock strata to upper water aquifer to cause contamination. In addition, the spalling of overburden strata and unbalance hydrostatic pressure in the surrounding area of the UCG cavities could also create paths for the aquifer water to flow into the cavities, mix with the residual chemicals produced in UCG process, and consequently contaminate the upper aquifers. An example is the detection of benzene in ground water in Kingaroy project in Queensland which directly caused the project to be blocked in July of 2010 (Imran et al., 2014).

During the UCG process, elevated temperature and permeation of fluid inside the rock pores could change the mechanical behaviour such as stiffness and strength of strata rock, which might cause geologic instability and even substantial subsidence of the ground surface. An investigation by Vorobiev et al. (2008) at LLNL has focused on geomechanical processes in coal and surrounding rocks during the UCG process. Finite-element (FE) and discrete-element (DE) are coupled both in two and three dimensions to analyse a series of UCG scenarios.  For example, the collapse of cavity roof as a result of blocks sliding into the cavity under the stress induced by the cavity was simulated by introducing joints into the continuum FE model (see Figure 3.8).

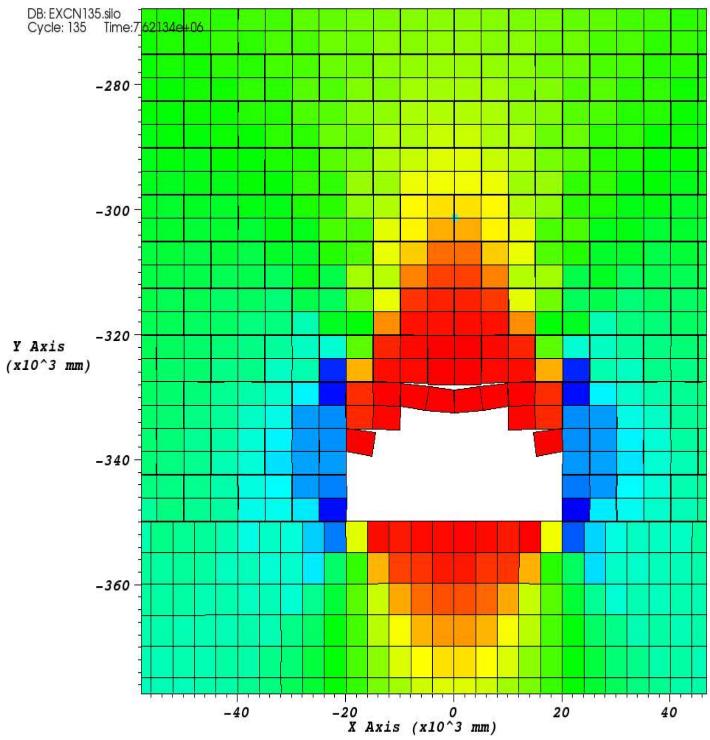
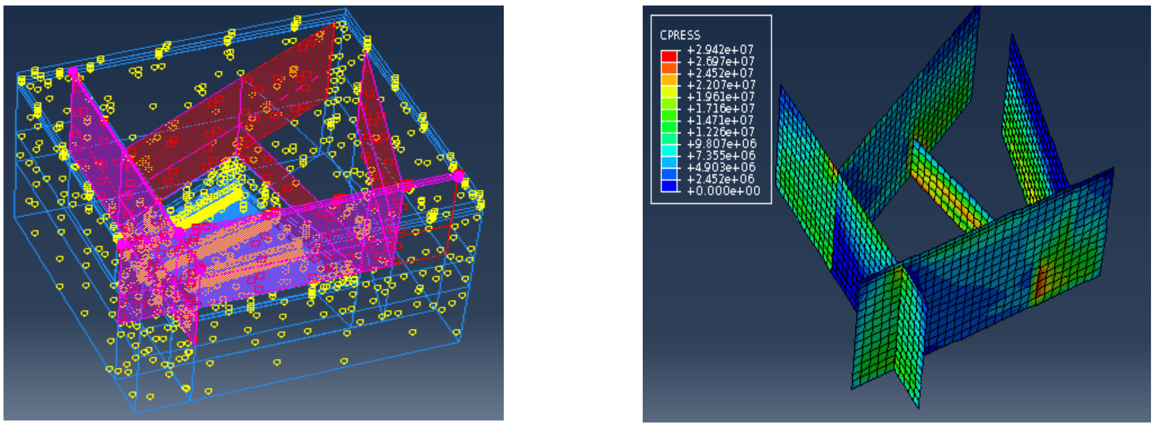



Figure 3.8 Collapse of Cavity in jointed rock during UCG, after Vorobiev et al. (2008).

In a recent EU project funded by RFCS, the geomechanical response of the geologic faults in a potential UCG coal deposit was studied (Sheng et al., in press). The model incorporated a detailed geologic structure of the site including the positions and depths of the faults as well as the thickness of and depth of the coal seams, as shown in Figure 3.9. A sensitivity analysis on the acceptable distance of the cavity away from the faults has been carried out and the resulted stress distributions are used as one of the criteria for the site selection.




(a) (b)

Figure 3.9 Geomechanical model of the selected site: (a) faults structure in pink and (b) Contact pressure distributions on the faults

Besides the numerical modelling on UCG cavity growth and gas flow, the consequent effects of UCG on the subsidence and water flow are also important factors to consider. In addition, to minimize the environmental impact, after shutting down the UCG process the cavities must be washed by a net flux of water. This operating strategy prevents the dispersion of reaction products into the surroundings in preparation for post-burn clean-up treatment which is particularly important when $CO_2$ is planned to be injected back. The temperature, pressure, porous media properties, and composition of the liquid and gaseous phases (including contaminant concentrations in the groundwater) in the subsurface after the UCG need to be addressed. A 3D regional groundwater model was developed using the computer program MODFLOW to investigate the non-isothermal groundwater flow and contaminant transport near a vertical geologic fault (benzene was considered to be the primary contaminant of concern) (Sheng et al., in press). The modelling results in Figure 3.10 showed that contaminant concentrations would exceed 1 ppb after one year of UCG operations but in a relatively small area in the vicinity of the impacted zone. For the later years, the concentrations would be substantially below 1 ppm due to contaminant dilution.

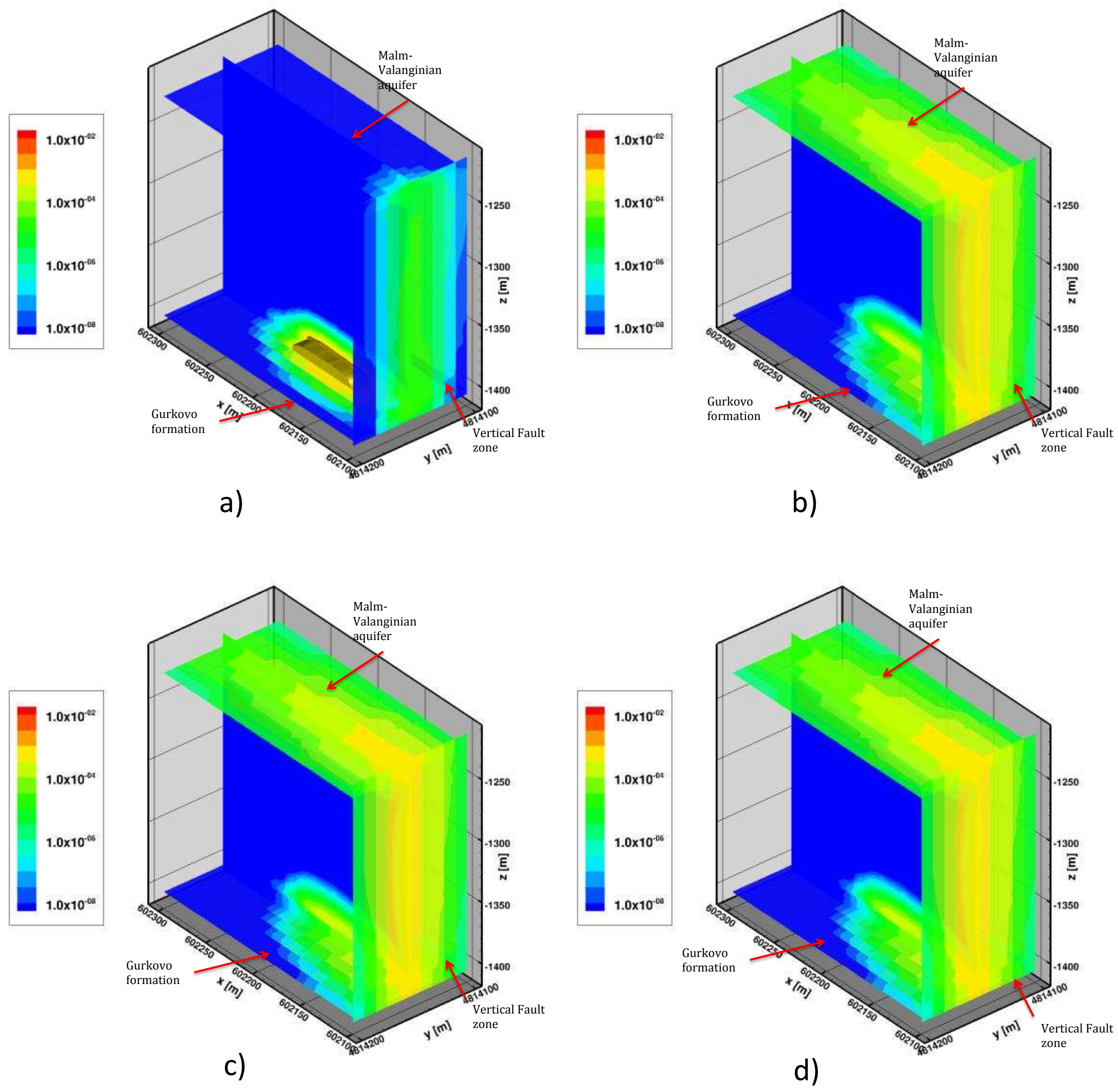



Figure 3.10 Model predicted transients in benzene concentrations in ppm.

(a) 1 year, (b) 10 years, (c) 100 years and (d) 1000 years after the UCG and CCS activities have been performed

To address the issues of rock fracture, aquifer interference, and water flow in coalmine environment, CSIRO (Commonwealth Scientific and Industrial Research Organisation) in Australia has developed a two phase flow model based on finite element method, COSFLOW (Mallett, 2006). In COSFLOW, the fracture is estimated from a mechanical sub-model and coupled with the changes of permeability and porosity used in the fluid flow sub-model. Similar to the conventional flow model, the flow in the fracture system is controlled by the pressure gradient and is governed by Darcy's law. The dynamic interaction between the mechanical deformation and fluid flow processes is described through a series of coupled non-linear partial differential equations. A prediction result of subsidence and permeability is shown in Figure 3.11 and Figure 3.12, respectively.

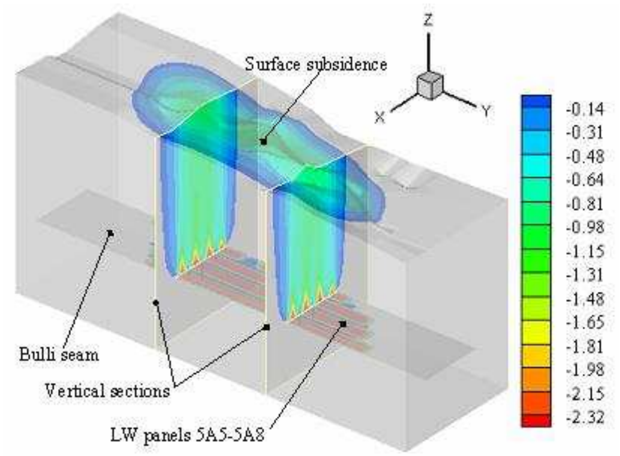



Figure 3.11 Modelling of subsidence by COSFLOW

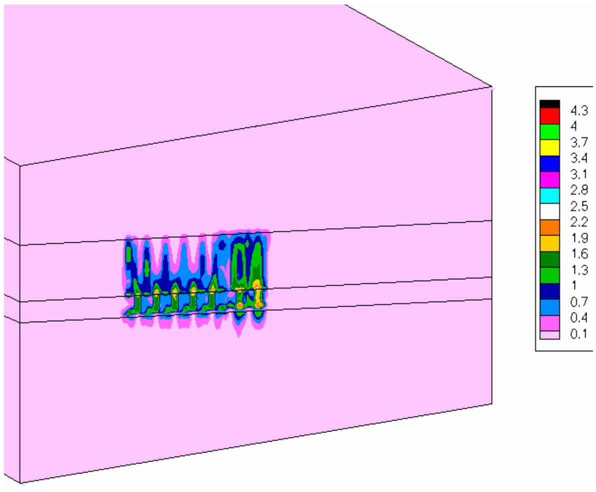



Figure 3.12 Modelling of permeability by COSFLOW

### 3.2.4 Integrated modelling

Aghalayam (2010) reviewed the state-of-the-art modelling of UCG process and reported that a few models have considered three-dimensional simulation of the UCG process with some assumptions, such as the absence of the heat-transfer calculation or constant gasification temperature. A distinguishing feature of three-dimensional modelling is that the physical and chemical phenomena, such as mass and heat transport, chemical reactions, and geo-mechanical behaviour, become far more complex. UCG involves interdependent multi-physical/chemical processes (Figure 3.13) in which the cavities, geologic deformation and fracture, as well as fluid permeation take place at different time and length scales. LLNL has been developing a new integrated 3D UCG simulator with the capability to predict cavity growth, product gas composition and rate as well as environmental interaction (Nitao, 2011). The model aims to integrate thermal-hydrological model, cavity gas model, geomechanical model, rubble zone model, wall zone model and boundary evolution model. It has been applied to modelling the Hoe Creek III field test with encouraging results demonstrated in Figure. 3.14.

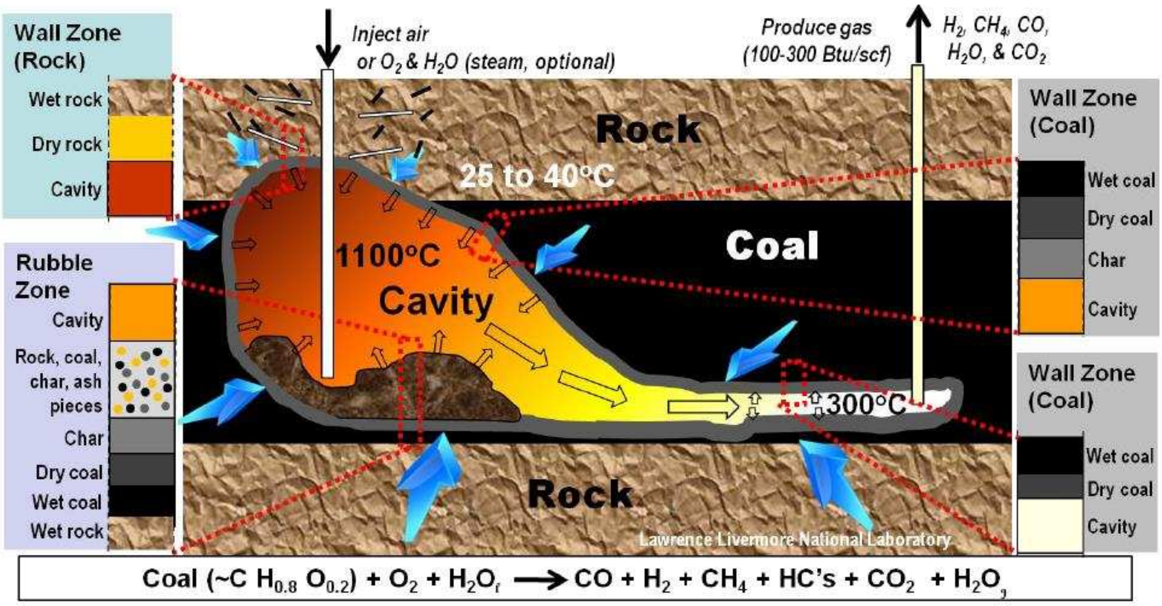



Figure3.13 Distinctive multiphysical/chemical process domains involved in UCG(Nitao, 2011).

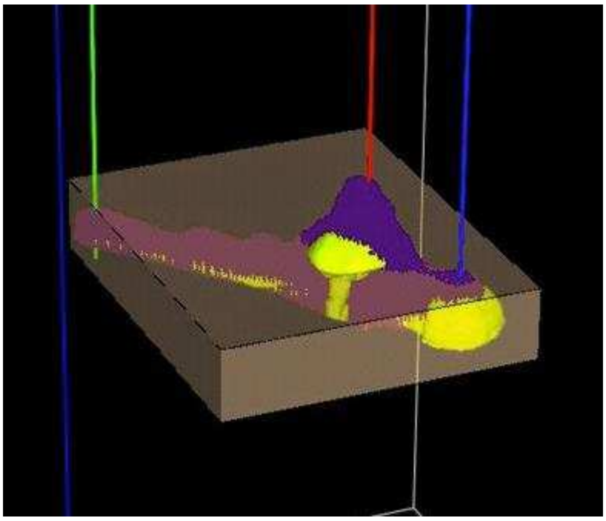


Figure 3.14 Integrated modelling of UCG cavity at 14 days (Nitao, 2011).

**4. Combining UCG with CCS**

Although there has not been a trial test on UCG-CCS, the methods of capaturing CO2 from UCG syngas have been discussed, including pre-combustion removal, post-combustion removal and oxy-fuel method (Zamzow, 2010). It is assumed that UCG would leave highly porous residuals and adjacent coal seams, in addition to the cavity voids. As these areas cool down, the abandoned cavities would be accessed by directional drilling or through the existing production boreholes. $CO_2$ would then be injected at high pressure for storage and retention. For permanent $CO_2$ sequestration, the depth and strata conditions must be suitable. When a UCG operation is shut down and $CO_2$ is scheduled to be injected back to the cavities, it is essential to carry out the necessary treatments to prepare the cavities for an efficient $CO_2$ storage, while preventing contamination of adjacent groundwater aquifers. With cavities cleaned, potential contamination of nearby aquifers caused by the escape of UCG by-products (tars, phenol, benzene, etc.) could be avoided. Furthermore, after the UCG process, the temperature in the UCG reactor remains as high as 1000 °C for a long period. At the time of $CO_2$ injection, the temperature in and around the UCG cavities must have already been cooled down to a temperature level to maintain the $CO_2$ in a supercritical status. Cavities can be cooled down either naturally (without any specific measures) or by flushing water. A coupled hydro-thermal analysis was carried out to investigate time dependency of the cooling down process, showing that the forced cooling by water flushing at a flow velocity of 1 m/s can decrease the temperature in the cavities much more efficient than natural cooling at a factor of more than 300 (Sarhosis et al., 2013). However, a coupled thermo-hydraulic-geomechanical model is still required to investigate whether the forced cooling could induce fracture events in the rock strata. Other factors that must be considered when combining UCG with CCS are well completion, site selection criteria to minimize environmental impacts after $CO_2$ injection, and economic feasibility of injecting $CO_2$ into UCG cavities.

The volume required to store the $CO_2$ produced from the combustion of syngas can be 4 to 5 times larger than the volume occupied by the extracted coal at 800 metres depth, but the actual storage capacity of is much higher than the extracted coal volume because of the increased permeability of the rock strata as well as the remaining coal between the UCG cavities and between gasification channels (Roddy et al., 2010). Accurate prediction or estimation of the $CO_2$ storage capacity in UCG cavities is challenging, and it directly affects the technical feasibility of UCG-CCS projects. The $CO_2$ sorption capacities of coal gasification residues for representative hard coal in Germany was experimentally measured by Kempka et al. (2011) which provides an effective assessment of the $CO_2$ storage potential related to the UCG-CCS technology. It was found that up to 42 percentages increase of $CO_2$ sorption capacity before and after gasification, suggesting that storage of $CO_2$ in UCG cavities is a feasible option.

Economic cost is another important factor that also needs to be considered when combining UCG with CCS. A techno-economic model has been developed by Nakaten et al. (2014a; 2014b) to assess the one-at-a-time sensitivity of the cost of electricity on 14 selected geological, technical and market-dependent variables in a UCG-CCS process where synthesis gas from UCG is used to fuel a combined cycle gas turbine (CCGT) for generating electricity. It was revealed that the cost of electricity is less sensitive to geological model input parameters than the technical components of CCGT implementation, the syngas composition or market-dependent parameters in the selected study case. It was calculated that the overall cost of electricity accounts to 48.56 €/MWh without CCS or emission charges. However, the cost increases significantly to 71.67 €/MWh according to a CO2 storage capacity of 20.5% in the UCG cavities and a CO2 emission charge of 80 €/t, and to 73.64 €/MWh with 100% emission charges, thus further CO2 storage options would be more economic. The model is site-specific for a target area in Bulgaria, but it is applicable to any potential UCG site for economic analysis, provided the geological, hydrogeological and geomechanical data are available.

Interdisciplinary studies on the technical and economic feasibility of combining UCG with $CO_2$ storage in a Bulgaria coal deposit was presented with a focus on the development of site selection requirements for UCG-CCS, estimation of $CO_2$ storage volumes, drilling and completion issues for wells used for UCG and/or subsequent $CO_2$ injection, and assessments of economic feasibility and environmental impacts of the scheme (Sheng, Y., et al., in press). State-of-the-art geological, geo-mechanical, hydro-geological and coupled thermo-mechanical models were developed to better understand the UCG-$CO_2$ storage processes and aid the determination of site selection requirements for evaluation of deep coal locations in a target coal deposit in Bulgaria. A set of criteria for the UCG site selection are listed in Table 4.1. The risks of subsidence and groundwater contamination have been assessed in order to pave the way for a full-scale trial and commercial applications. The research confirms that cleaner and cheaper energy with reduced emissions can be achieved by combining UCG with CCS and the economics are competitive in the future European energy market. However, rigorous design and monitor schemes are still essential for productivity, safety and the minimisation of the potential environmental impacts.

Table 4.1 List of criteria from hydro-geological investigations

| Category | Desired value | Comments |
|---|---|---|
| Coal thickness (m) | >2m | Not greater than 30m. Ideally 5 -10 m |
| Number of seams to be gasified | | Avoid seams with overlying coal within 15m |
| Thickness variation (% of seam thickness) | <25 | Avoid variable thickness seams |
| Depth (m) | >92 | Preferably more than 300m and not more than 2000 m |
| Angle of coal seam (degrees) | 0-70 | Any but steeper is preferred as it may be technically difficult to mine through conventional methods. |
| Variation of the angle of the coal seam (% of average angle) | <2 | |
| Thickness discontinuity (m) | 1 | Avoid seams with variable partings/ discontinuities. |
| Overburden (m) | 100 | Floor and roof conditions needs to be examined carefully. |
| Coal rank (vitrinite reflectance) | Low rank bituminous | Free swelling index should be low. Sub bituminous or lower rank, ideally not coking, non-swelling coals. |
| Ash content (wt %) | <50% | |
| Coal sulphur (wt %) | <1 | Volatile matter greater than 10%. Sulphur should be removed along with syngas. |
| Coal moisture (wt %) | <35 | Preferred 7-35%. Controlled inflows of water or high moisture contents are desirable especially after ignition. |
| Gross calorific value of coal | >12MJ $kg^{-1}$ | |

| Category | Desired value | Comments |
| --- | --- | --- |
| Thickness of consolidated overburden | >15 | |
| Seam permeability (mD) | 50-150 | More permeable greater than 20%. Swelling coals may interrupt the gas circuit. High permeability coals may allow excessive water infiltration causing possible chance of gas leakage and contaminant movement. |
| Porosity of coal seam | >30% | Porous coal seam. |
| Distance to nearest overlying water-bearing unit (m) | 100 | |
| Coal aquifer characteristics | Confined | |
| Available coal resources (106 m3) | >3.5Mt | >20 years long operation. Depend upon gas utilisation and profitability. |
| Proximity to faults | >150 m depending on site conditions | If many major faults then site specific calculation required to be carried out for the accurate estimation of the distance. |
| Distance from active mines (km) | >3.2 | |
| Distance from abandoned mines (km) | >1.6 | |
| Geology-lithology | | High UCS, non-porous and impermeable strata |
| Hydrology | Non aquifer strata is preferred. | Non porous strata <30%, Impermeable <5%, Moderate water ingress. Avoid potable aquifer and large water bodies. |
| Geotechnical strata properties | Rock strength: Uniaxial compressive strength range 50 to 250 MPa. Density greater than 2000kg/$m^3$ | Avoid excessively fractured, faulted and broken rocks as they may cause water inrush or product gas and contaminant leakage |
| Infrastructure availability | | Roads, electricity and power transmission lines |
| Presence of coal bed methane | | Depends upon economics or commercial value of CBM deposit and its interoperability with UCG. |

## 5. Discussion and conclusions

UCG could be an attractive and green technology for the utilisation of huge unminable coal resources to produce syngas products (e.g. power generation, coal to liquids, hydrogen and fertilizers) with distinct economical and environmental advantages. UCG also provides an opportunity for low cost CCS as it does not require the transportation of $CO_2$. However, modern UCG is a new industry to the public, the media and also the regulators. Though licensing policies for UCG are already being formed in some countries (e.g. Australia, UK, Canada, New Zealand and U.S.A), the lack of regulations in other countries is slowing down the progress. The challenge to ensure the commercial viability of UCG technology is still significant, but these hurdles could be overcome by contributing more research efforts as well as deploying the right policies and arguments to convince the public. While government support of the technology is needed to produce a reliable base of technical knowledge and expertise, the implementation of more projects is required to test possible UCG approaches and practice the combination of UCG-CCS. Additionally, some commercial field projects could serve as possible locations to develop and test novel monitoring, simulation, drilling or environmental protection technologies, tools and approaches. Existing computational models are very helpful for improving the understanding of UCG process and can provide certain guidance on better controlling of it, however, considerable work still needs to be done on developing more advanced and more integrated computational models that are validated at laboratory scale as well as field scale to more accurately predict the cavity growth and the environmental impact of UCG and subsequent $CO_2$ injection and storage. This will not only gain more confidence from the public for future UCG-CCS projects but also provide useful guides on the selection of potential UCG-CCS sites. CCS research and development is active and demonstration scale projects of both capture and $CO_2$ storage in saline aquifers and depleted hydrocarbon fields for enhanced oil or gas recovery are underway worldwide, but combining UCG with CCS is still at a stage of desk study and feasibility investigation.

When $CO_2$ is injected into the UCG cavities, an important issue to be addressed is the upward movement of $CO_2$ as a free phase (free surface flow). During the injection of $CO_2$ into the deep underground cavities, increased formation pressure as well as temperature difference between the injected $CO_2$ and caprock as well as remaining coal will change the effective stress condition in the geologic structure. In addition, large buoyance forces together with hydrocarbon depletion on overlying caprock might challenge its capillary and structural integrity and can eventually trigger seismic events. The understanding of coupled thermo-hydro-mech-chemical effects will be crucial to convince the public that $CO_2$ injection and storage is secure. The geologic response as a result of interactions between the injected $CO_2$ and the storage complex must be taken into account in order to identify and prevent the potential leakages during the injection and storage phases. Integrated models can aid in defining the maximum sustainable injection pressure that guarantees that no $CO_2$ leakage will occur. The permeation of $CO_2$ into caprock is determined by the combined effects of $CO_2$ pressure distribution as well as the rock permeability. Therefore it is important to understand how the $CO_2$ penetrate into and propagate within the caprock under dynamic (during injection) and equilibrium (after injection) pressure conditions. The storage Of $CO_2$ in UCG cavities is different to other CCS approaches, thus it is essential to carry out trial projects to test the UCG-CCS concept and collect field data for further research development including the cross validation of computational models and field measurements.

In addition to the technical challenges involved in UCG-CCS, economic assessment has rarely been undertaken to determine the costs of energy produced by UCG syngas with the consideration of subsequent $CO_2$ storage. An reliable model for economic assessment rely on the detailed geomechanical, geological and hydrogeological data of a target coal deposit, which cannot be obtained without the engagement and investment from industry and government. In addition, the $CO_2$ storage requires long-term monitoring and maintenance, which creates more difficulties and uncertainties for predicting whether a UCG-CCS project is economically worthwhile. Nevertheless with both UCG and CCS technologies being more mature, the combination of these two will eventually become technically and economically viable.

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