THE POTENTIAL FOR UNDERGROUND COAL GASIFICATION IN INDIANA

Phase I Report
to the
Indiana Center for Coal Technology Research (CCTR)

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1 Project Description

1.1 Project rationale

Currently, Indiana mines over 35 million tons of coal a year, or about 3.5% of total U.S. coal production. The potential energy of Indiana coal reserves exceeds that of US oil and gas reserves. Indiana, however, generates only half of its coal-fired electricity using its own coals and imports over ten times the coal tonnage than it exports. Owing to some of the advantages that are inherent in the process, such as relatively easy sulfur removal, the gasification of coal is being assessed as one of the options for the future use of Indiana coals. The gasification process produces syngas (a CO/H_2 mixture), which can be used for the generation of electricity or for the production of liquid hydrocarbon fuels, natural gas surrogates and other valuable chemical products. Although CO_2 is also generated during the process, advanced coal gasification methods include solutions for carbon capture with lower costs than in conventional coal-fired power plants. Carbon sequestration will likely be mandatory in newly constructed power plants.

Earlier feasibility analyses focused on the construction of new coal gasification plants in Indiana. Meanwhile, there exists an alternative method, called ***underground coal gasification*** (UCG), in which injection and production wells are drilled from the surface and linked together in a coal seam. Once linked, air or oxygen is injected and the coal is ignited in a controlled manner. Water present in the coal seam flows into the cavity formed by the combustion and is utilized in the gasification process, which produces primarily H_2, CO and CO_2. The produced gases flow to the surface through one or more production wells and are then cleaned for power generation and/or liquid hydrocarbon synthesis.

The UCG process has great advantages over surface coal gasification such as lower capital investment costs (due to the absence of a manufactured gasifier), no handling of coal and solid wastes at the surface (ash remains in the underground cavity), no human labor underground, minimum surface disruption, and the direct use of water and feedstock "in place". In addition, cavities formed as a result of UCG could potentially be used for CO_2 sequestration.

The UCG process, however, has potential problems that must be addressed before commercialization can occur. They include difficulties in linking the injection and production wells, insufficient thicknesses of coal seams, variation of product gas composition, groundwater pollution, potential subsidence and a lower heating value of the produced gas as compared with coal when combusted (which may make it uneconomical to transport over long distances). In addition, well-known accidents with uncontrolled underground coal fires, such as that near Centralia, PA, cause public concerns about potential loss of control over the UCG process. Fortunately, it appears that all these problems can be resolved. For example, a reliable link between the two wells can be established by appropriate selection of specialized "linkage technology." The thickness, depth, and character of coal seams can be determined based on geological data. To control the product gas composition, the process parameters (e.g., injection pressure and flow rate, oxygen concentration) can be adjusted according to real-time surface measurements. Groundwater can be protected by conducting the UCG process at pressures below hydrostatic pressure and using the water that exists within the coal seam when total dissolved solids content is greater than 10,000 ppm. Transportation costs can be decreased by the optimum selection of potential UCG sites and by construction of power-generating or chemical plants near the UCG locations.

This brief review demonstrates that UCG promises great potential benefits, but careful analysis of Indiana's geology, coal properties, water resources, etc., coupled with the survey of UCG state-of-the-art, must be conducted to identify potential UCG sites and to determine the feasibility of employing this technology in Indiana. To conduct this analysis is the goal of this project.

1.2 Plan of work

The plan includes three phases:

Phase 1 (April 1, 2008, - August 31, 2008)

Analysis of UCG current state of the science and technology (globally) and determination of criteria required for selecting suitable locations for a project.
Responsibility: Purdue

Phase 2 (September 1, 2008, - November 30, 2008)

Analysis of Indiana's coal resources and determination of suitable UCG locations.
Responsibility: IGS (a sub-contractor in the current project)

Phase 3. (December 1, 2008, - January 15, 2009)

Integration of results of Phases 1 and 2, final scoping report Selection of the most promising UCG locations.
Responsibility: Purdue and IGS

<u>Phase 1: Analysis of UCG current state of science and technology and determination of criteria for site selection</u>

The analysis of UCG state-of-the-science and most current technologies that are being employed globally was conducted based on extensive search of the literature, including journal articles, conference proceedings, patents and Internet publications. It should be noted that UCG has been used commercially in the former Soviet Union; thus, along with English language texts, the papers and patents written in Russian were also analyzed. Along with the literature search, it is expected to obtain useful information from active UCG experts. In the US, researchers at Lawrence Livermore National Laboratory (LLNL) have wide experience in studies of UCG and carbon sequestration. Thus, it is proposed that one or more members of Purdue team will visit LLNL for consultations. It is also planned that two members of the Purdue team will attend the 25th Annual International Pittsburgh Coal Conference, where UCG is among the symposium topics.

The UCG analysis was focused on the determination of selection criteria for available coal resources. The Indiana Geological Survey (IGS) in Bloomington, IN, has a defined set of criteria for underground mining, which include technological and land-use restrictions, but some of the criteria for UCG may be different. For example, the UCG process has specific requirements for the depth and thickness of coal seams that differ from those that constrain mining. Based on the criteria that have been applied at other UCG projects around the world, the information that the IGS has in its records will be used to constrain the potential locations for projects within Indiana. The available information on the minimum seam thickness for UCG is contradictory and this criterion was established taking into account the specifics of the Indiana coals. Also, it is unclear how partings, splits and other characteristics of the coal seam may influence UCG process and affect the criteria. It is expected that to clarify these issues, mathematical modeling may be required (which, however, may need to be developed further in a follow-up study). Further, water is an essential component of UCG process, and thus its presence within a coal seam and the adjacent rock formations is an important characteristic. Finally, along with the technological restrictions, the land-use restrictions may also be different for UCG, as compared with underground mining. Some environmental issues in UCG are also different from those in mining, which leads to different restrictions.

The Phase 1 Report, including the list of criteria for UCG (see chapter 3), determined by the Purdue team, will be forwarded to the IGS team and to CCTR.

Phase 2: Analysis of Indiana's coal resources and determination of suitable UCG locations

Using the available database of Indiana coal resources and characteristics, the IGS team will create maps to identify locations that match the UCG criteria. For the suitable locations, additional important information will be provided, such as coal heating value, concentrations of sulfur, mercury and other impurities, the feasibility to use the UCG cavities for CO_2 sequestration, as well as the availability of other potential sequestration locations.

The Phase 2 Report, including the list and characteristics of suitable UCG locations, determined by the IGS team, will be forwarded to the Purdue team and CCTR.

Phase 3: Selection of the most promising UCG locations

It is expected that Phase 2 will determine certain locations that are suitable for UCG. They will be analyzed during Phase 3 by the Purdue team, together with the IGS team, to select the most promising UCG locations. In particular, infrastructure issues will be considered, such as transportation of the produced syngas to the Wabash IGCC power plant and construction of power and chemical plants near selected UCG locations. Special attention will be paid to environmental aspects, including the risks of groundwater pollution and uncontrolled combustion.

The Final Report, including the list and characteristics of the most promising UCG locations, will be forwarded to CCTR. In the final report, the current status of UCG will be described and the feasibility to use UCG in Indiana will be determined, along with identification of the most promising locations and a list of characteristics for each that allow comparison and selection.

1.3 Deliverables

Interim Report (Phase 1) Delivery Date: August 31, 2008. Responsibility: Purdue
Interim Report (Phase 2) Delivery Date: November 30, 2008. Responsibility: IGS
Final Report Delivery Date: January 15, 2009. Responsibility: Purdue and IGS

Interim Report (Phase 1) Presentation Date: the Panel meeting on September 11, 2008[1]
Final Report Presentation Date: the first Panel meeting in 2009.

[1] Meeting canceled; new presentation date to be established.

2 Analysis of UCG Current State of Science and Technology

2.1 USSR (before 1991), Russia, Ukraine and Uzbekistan (after 1991)

In the former Soviet Union, an intensive research and development program on UCG was conducted from the 1930s, leading to the operation of several industrial scale UCG plants in the 1950s, with scales of operation being up to 300MW$_e$ equivalent. The produced gas was locally distributed for industrial use. In the 1960s, five UCG gas production stations were operating and as many as 3,000 people were involved in UCG research and development. In Yuzhno-Abinsk (Kuznetsk Basin, Russia), a UCG station produced combustible gas for 14 boiler plants in the city of Kiselevsk from 1955 until closing due to equipment deterioration in 1996 (Kreinin, 2004). In Angren, Uzbekistan, an UCG-based power plant is still in operation after ~50 years (Fig. 1). This plant, however, is the only commercial UCG site now in the independent states formed after the FSU collapse. It is generally believed that UCG in FSU declined in 1970s due to the discovery of extensive natural gas resources in this region. Yet, over 15 million metric tons of coal have been gasified underground in the FSU generating 50 billion m^3 of gas (Kreinin, 2004). For comparison, 50 thousand tons and 35 thousand tons of coal have been gasified in the US and Australia, respectively.


Figure 1. Images of Angren UCG-based power plant (http://www.lincenergy.com.au).

Gregg and Edgar (1978) have provided a comprehensive review of UCG R&D in the USSR from the 1930s to 1970s. Later, detailed reviews were published in the Russian language (Kreinin et al., 1982; Antonova et al., 1990; Lazarenko and Kreinin, 1994). Recent monographs by Kreinin (2004) and Lazarenko and Kreinin (2006) also review old Soviet UCG activity and, in addition, include information on recent work in Russia. It appears that major technical problems of UCG were successfully solved by researchers and engineers in FSU, leading to the aforementioned commercial developments.

In particular, one problem of UCG technology is the necessity to ***link the injection and production wells***. If the coal has high permeability or fractures, a channel between the wells might exist naturally. In many cases, however, the coal seam has low permeability, and a linkage technology is necessary. After testing different methods for linking the injection and production wells, rather reliable and relatively inexpensive technologies were developed, such as hydraulic fracturing of the coal seam by pressurized air (or water) and the so-called reverse combustion (ignition near the production well and countercurrent flame propagation). It should be noted that in the 1990s, advanced methods for directional underground drilling were developed in the oil and gas industries, which may compete successfully with these technologies. Nevertheless, they remain attractive due to relatively low costs, and can be used either alone or in combination with drilling (for more detail, see Section 2.11).

The results of UCG R&D in FSU are important for the selection of UCG sites. For example, it was shown that the UCG process based on injecting air produces fuel gas with relatively low heating value, limited to 4.6-5.0 MJ/m^3 (123-134 BTU/cft) and typically is 3.3-4.2MJ/m^3 (89-113 BTU/cft) (Kreinin, 2004). Long-distance transportation of this gas is economically inefficient, thus, the best way is to use it (for power generation or for conversion to other products) near the UCG site, preferably not farther that 25-30 km (15-20 miles) (Kreinin, 2004). This should be an important factor in the selection of UCG sites in Indiana. Note, however, that the heating value of the produced gas can be increased by oxygen enrichment of the injected air. This was demonstrated, for example, in UCG station in Lisichansk (Donetsk Basin, Ukraine) where cheap oxygen was available as a byproduct of inert gas production (Kreinin, 2004). Use of steam and O_2 injection increased the heating value of the fuel gas to 10-12 MJ/m^3 (268-322 BTU/cft) (Kreinin, 1992). Although the use of oxygen increases the costs, it can remain economically feasible.

Another important result is related to the ***coal seam thickness***. It was shown that the detrimental effect of the surrounding formation (due to heat loss by thermal conduction) on the heating value of the produced gas becomes significant as the seam thickness falls below 2 m (Fig. 2). This conclusion is important for analysis of UCG feasibility in Indiana, where most coal seams are thinner than 1 m. Note, however, that there are coal sites in Indiana with seam thickness more than 1 m and even more than 2 m. Thus, it is possible that there are Indiana sites where the coal seams are sufficiently thick and also satisfy the other UCG criteria. Identification of such sites is the goal of this project.

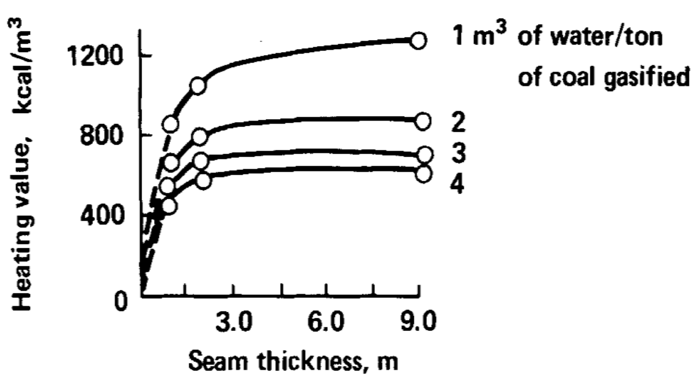

Figure 2. Effect of seam thickness and the specific water inflow into gasification zones on the heating value of gas obtained by UCG (Gregg and Edgar, 1978).

Kreinin (2004) highlighted 10 achievements of UCG researchers and engineers in FSU:

1. Linkage technology based on reverse combustion.

2. Linkage technique based on hydraulic fracturing of the coal seam.

3. Methods for widening narrow (0.15-0.2 m) initial channels to diameters more than 0.5 m; determination of optimum conditions for combustion-based widening.

4. Analysis of the obtained experimental and technological data has allowed determination of a quantitative relationship between the gas heating value, coal heating value, gas yield, seam thickness, water inflow rate and coal gasification rate. The obtained empirical equation is:

$$I = \frac{v}{0.506 \cdot \left(\frac{Q_g \cdot V_g}{Q_c} \right) h^{\left(0.702 - 0.659 \cdot \frac{Q_g \cdot V_g}{Q_c}\right)}} \quad , \qquad (1)$$

where I is the gasification rate, ton/hr, v is the water inflow rate, m^3/hr; Q_g is the gas heating value, MJ/m^3; Q_c is the coal heating value, MJ/kg; V_g is the gas yield, m^3/kg; h is the coal seam thickness, m; and 0.506 is an empirical coefficient, m^{-1}.

5. It was shown that direct feed of air (or oxygen) to the reacting surface in the UCG reactor improves the process efficiency.

6. A technique was developed to calculate optimum hydrodynamic regimes in the underground gas generator for various geological conditions.

7. The mechanisms of rock movements during UCG were determined and methods to control this movement were developed.

8. The influence of hydrogeology on the UCG process was studied, and drying techniques were developed which account for specific geological conditions. Based on studying the migration of groundwater in the UCG zone, ecological principles were formulated.

9. Criteria for selection of UCG sites, accounting for geological features of coal beds and surrounding rocks in various regions of FSU, were formulated.

10. Monitoring of the ecological situation, including groundwater pollution, rock deformations and harmful gas emissions, was conducted for many years in active UCG plants.

The results of environmental monitoring can be illustrated by the example of Yuzhno-Abinsk Podzemgaz station in the Kusbass, where increases in phenol concentration and water temperature were observed, but it was concluded that water pollution during UCG was of a local nature and by admissible concentrations of noxious compounds. Specifically, phenol concentrations in the spent reactors achieved a maximum of 0.17 mg/L, but in the surrounding area, water sampled from 18 monitoring boreholes contained 0.0007-0.0042 mg/L phenol (Kreinin and Dvornikova, 1994).

The UCG R&D in the FSU has included mathematical modeling of the gasification process. A model has been developed which takes account of the principal gaseous reactants and products in a gasification channel of known geometry and water influx. The model predicts gas outputs using air injection at various flows and pressures. The results of the model are reported to be in good agreement with measured data from UCG trials (Kreinin and Shifrin, 1993).

Other research has assessed the effects of UCG on the immediate strata. Results indicate the pattern of roof deformation in UCG and the filling of cavities with caved rocks is intimately linked with the physical, mechanical and thermal properties of the rock. At temperatures of

1000-1400°C rocks may deform, swell and expand (Den'gina et al, 1994). In general, rocks cooled after heating (annealed) have improved strength properties.

Models for interaction of gaseous products with groundwater have also been developed. It is noted, however, that to create a reliable automatic control system for UCG, it is necessary to develop a comprehensive model which combines the aforementioned models for the gasification process, roof deformation and gas-water interaction (Kreinin, 2004).

Currently, along with continuing operation of the UCG plant in Uzbekistan, research and development of UCG is continued in Russia and Ukraine. Figure 3 shows the number of patents in the UCG area for different countries over the last 20 years. This analysis was conducted using the database of the European Patent Office. Using the database of the World Intellectual Property Organization (WIPO) produced identical results. It is seen that after some period of inactivity, chronologically corresponding to the worst economic conditions in the FSU, UCG R&D is currently being reactivated in Russia and Ukraine.

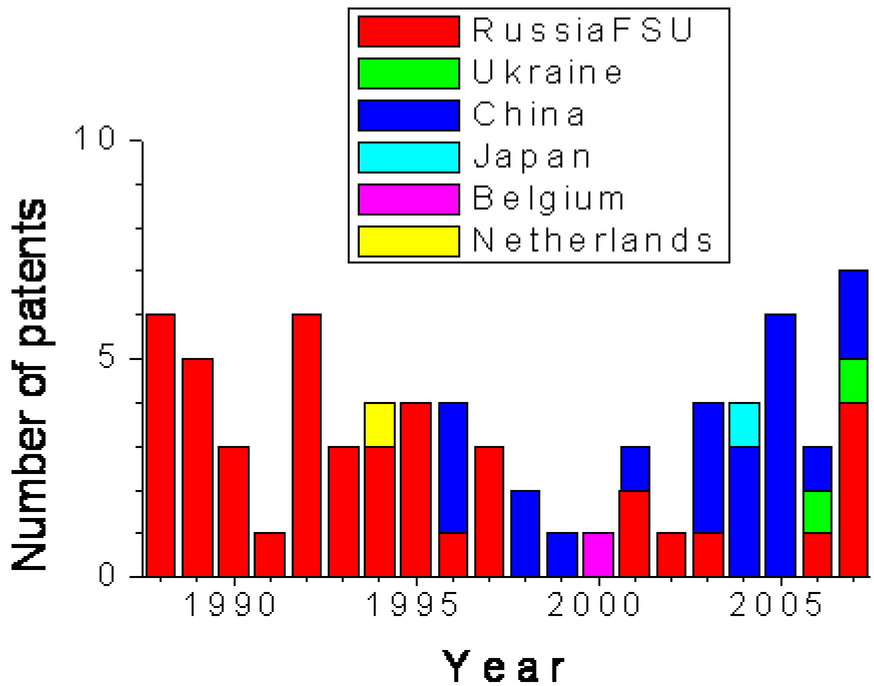

Figure 3. Number of patents in the UCG area for different countries for the last 20 years (the year indicates the year of patent publication).

Novel applications have been identified such as the development of mobile UCG units capable of supplying gas to remote agricultural areas. It was shown that Stirling engines would be very attractive in combined heat and power units using UCG gas (Arens et al., 2007). The same authors also proposed to use cycling combustion and heat accumulation in such units; these developments include solutions for separation of dust from the UCG gas, as well as for capturing CO_2 and sulfur from the combustion products.

It should be noted that, although all commercial UCG plants in FSU generated fuel gas for heat and power generation, research in Russia and Ukraine was also conducted on the possibility to use this gas for production of valuable chemical products such as gasoline and methanol (Kolokolov and Tabachenko, 1992).

2.2 United States

Initial UCG tests in the US were conducted in Alabama in 1940-1950s. Later, the UCG program was renewed and more than 30 experiments were conducted between 1972 and 1989 in various mining and geological conditions. Most of these were part of the DOE's coal gasification program, although some were commercially funded. With the exception of one trial site, experimentation has involved sub-bituminous coals. The US experiments included various diagnostics and subsequent environmental monitoring. In parallel to the UCG trials, 3-D computer models have been developed, particularly to simulate the cavity evolution, as well as to predict the effects of rubble (caved roof) consolidation on the injection process and drainage of water into the gasification zone from adjacent strata (Britten and Thorsness, 1989). The research in US has highlighted the importance of assessing the geological and hydro-geological settings for UCG.

Probably, the most important result of prior UCG work in the US is the development of the Continuous Retraction Injection Point (CRIP) process by investigators of the Lawrence Livermore National Laboratory (LLNL) (Hill, 1986; Burton et al., 2006). In the CRIP process, the production well is drilled vertically, and the injection well is drilled using directional drilling techniques so as to connect to the production well (see Fig. 4). Once the channel is established, a gasification cavity is initiated at the end of the injection well in the horizontal section of the coal seam. The CRIP technique involves the use of a burner attached to coiled tubing. The device is used to burn through the borehole casing and ignite the coal. The ignition system can be moved to any desired location in the injection well. The CRIP technique enables a new reactor to be started at any chosen upstream location after a declining reactor has been abandoned. Once the coal near the cavity is used up, the injection point is retracted (preferably by burning a section of the liner) and a new gasification cavity is initiated. In this manner, a precise control over the progress of gasification is obtained. The CRIP technique has been used in the Rocky Mountain 1 trial and later in the trial in Spain.

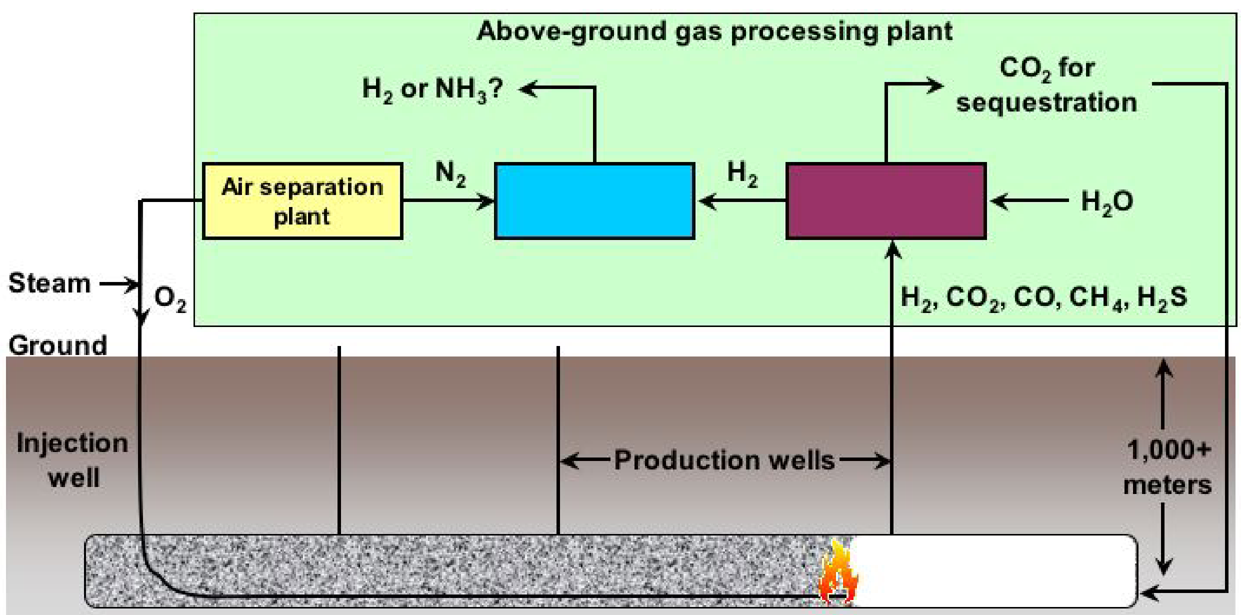

Figure 4. Schematic of the CRIP process (Burton et al., 2006).

After the discovery of cheap oil in the Middle East, large-scale UCG projects were not conducted in the US. The expertise, however, is maintained at LLNL and some other organizations. In recent years, due to growing energy needs, interest in UCG has been rejuvenated. BP and GasTech Inc. are developing an UCG demonstration project in the Powder River Basin (WY) that will be followed by a commercial-scale UCG project. In July 2007, BP and LLNL signed technical cooperation agreement on UCG. The initial two-year technical agreement will address three broad areas of UCG technology: carbon management to evaluate the feasibility of carbon dioxide storage underground; environmental risk assessment and management; and numerical modeling of the UCG processes to understand and history match pilot test results. The technical objective is for LLNL to provide BP with expertise, model results, new capabilities and insights into the operation and environmental management of UCG (http://www.syngasrefiner.com/ucg).

LLNL researchers highlight the importance of carbon management during the UCG process (Burton et al., 2006). It is noted that all three main approaches to CO_2 capture in surface power plants (pre-combustion, post-combustion and oxy-fuel) can be combined with UCG. There are two options for using geological CO_2 sequestration with UCG. One option is to use separate cavities for CO_2 storage and the other is to use the cavities that were formed during UCG. The latter option is attractive (for example, due to reducing costs for drilling, etc.) but there are limitations and problems that require further investigation (Blinderman and Friedmann, 2006). Note that since CO_2 must be stored in supercritical state, the cavity should be located deeper than 800 m.

2.3 Western Europe

A number of UCG tests have been carried out in Western Europe. A significant difference of these tests is the large depth of coal seams (600-1200 m, as compared with <300 m in FSU and US). The objective of tests in Thulin, Belgium (Chandelle et al., 1986; Kurth et al., 1986) was to develop the method of linking the wells for deep seams. The experiments were carried out between 1982 and 1984. The Thulin program was characterized by the utilization of special drilling techniques to achieve the links, which was successful. The CRIP method was used in one of the tests, and retraction of the injection point was demonstrated. Special corrosion resistant alloys were used in the well completion equipment.

In France, experiments were carried out during 1983-1984, initially at Bruay en Artois, and later at La Haute Deule (Gadelle et al., 1985). The objectives of these tests were to develop a better understanding of the coal reactivity and of the hydraulic properties of the linking between the wells. During these tests, operating conditions were determined for reverse combustion with limited risks of self-ignition. The experiments were discontinued because of plugging of the production well by particles and tars.

In 1992-1999, a UCG project of the European Union was conducted by Spain, the UK and Belgium at “El Tremedal” (Fig. 5) in the Province of Teruel, Spain, which was chosen based on its geological suitability, coal seam depth (550 m) and the availability of extensive borehole data (Pirard et al., 2000; Creedy et al., 2001). The objectives were to test the use of directional drilling to construct the well configuration and to evaluate the feasibility of gasification at depths greater than 500 m. The CRIP process was used for the trial. The Spanish trial was completed successfully. It demonstrated the feasibility of gasification at depth, the viability of directional drilling for well construction and intersection, and the benefits of a controllable injection and ignition point. The operating and drilling experience provided a number of useful lessons for future trials in terms of the detailed engineering design of the underground components, the control of the in-seam drilling process and the geological selection of trial sites.

Figure 5. A UCG trial facility at El Tremedal in northeast Spain in 1998. Image courtesy: Michael Green, UCG Partnership.

Largely as a result of the Spanish trial results, The Department of Trade & Industry Technology (DTI) in the UK identified UCG as one of the potential future technologies for the development of the UK's large coal reserves (DTI, 2004). An initial pre-feasibility study was completed in January 2000 by the DTI in conjunction with The Coal Authority, and work then began on the selection of a U.K. site for a drilling and in-seam gasification trial. Detailed work was done on the geological and hydrogeological criteria for UCG, the evaluation of suitable sites, and the legislative policies that would apply to an onshore UCG scheme. This work emphasized the growing importance of environmental issues, and a thorough investigation of these issues will likely be undertaken before legislative approval of a test site. Sury et al. (2004a, 2004b) provided a detailed analysis of the environmental aspects of UCG.

2.4 Canada

A small company, called Ergo Exergy Technologies Inc., located in Montreal, is providing UCG technology to several customers in different countries. According to the information on the company's web site (http://www.ergoexergy.com), prior to founding the company in 1994, the principals of Ergo Exergy worked at the Angren UCG plant in Uzbekistan. Recently, Ergo Exergy experts have completed a successful UCG trial in Australia (see Section 2.5). They are working currently for a UCG pilot plant in South Africa (see Section 2.6). They also collaborate with LLNL and BP.

It should be noted that, according to ErgoExergy, they use their proprietary εUCG™ technology. Burton et al. (2006) suggest the εUCG™ may be based on the old Soviet UCG technology. It appears that they may also use more recent approaches developed in Russia (for more detail, see Section 2.11).

Laurus Energy is an exclusive Canadian Licensee of the UCG technology provided by Ergo Exergy. Laurus Energy is developing its first commercial project based on UCG technology in North America. The project is targeting power generation and supply of fuel and hydrogen for the local industrial markets. Laurus Energy Inc. has large coal holdings in Alberta, Canada and started execution of its first Tomahawk I project development program, including regulatory and environmental approvals, site selection and pre-feasibility study, and site characterization program (http://www.syngasrefiner.com/ucg).

In addition, Dr. Michael Blinderman, Director of ErgoExergy, collaborates with researchers at the University of Queensland (Australia) in modeling the UCG process. Recently, they have developed numerical models for reverse and forward combustion regimes in UCG, and made stability analysis (Blinderman et al., 2007, 2008a, 2008b). Their results explain earlier experimental results and allow estimation of UCG parameters such as air consumption rate.

2.5 Australia

The development of UCG clean coal technology in Australia was strongly advocated by the late Professor Ian Stewart of the University of Newcastle. Prof. Stewart directed a program of laboratory test work, followed by a government funded feasibility study in 1983 into the production of UCG gas at the Leigh Creek coal mine in South Australia. The project study evaluated the use of the gas as a fuel for combustion in gas turbines. It concluded that such a project would be cost competitive with other sources of power.

As a result of reviewing this work and other international activities, a private company Linc Energy, Ltd., was formed to research, develop and commercialize the UCG process in Australia (http://www.lincenergy.com.au). Linc Energy conducted a UCG trial from 1999 to 2003 near the town of Chinchilla in Queensland, Australia, using the technology provided by Ergo Exergy (Blinderman and Jones, 2002). The Chinchilla project has demonstrated the feasibility to control UCG process, including shutdown and restart. The demonstration involved the gasification of 35,000 tons of coal and resulted in successful environmental performance according to independent audit reports. Results from an evaluation of the product gas composition showed that gas turbine units can operate satisfactorily on air blown UCG gas. The UCG operation in Chinchilla is considered to be the largest and longest UCG trial in the Western world. The major results are as follows:

- 35,000 tons of coal gasified;
- 80 million Nm^3 of gas produced at 4.5 - 5.7 MJ/m^3 (121-153 BTU/cft);
- a maximum capacity of 80,000 Nm^3/hr or 675 tons of coal per day was reached;
- availability of gas production over 30 months;
- 95% recovery of coal resource;
- 75% of total energy recovery;
- 9 injection / production wells;
- 19 monitoring wells;
- average depth of 140 m;
- high quality and consistency of syngas;
- no groundwater contamination registered;
- no subsidence has occurred;
- no surface contamination detected;
- no environmental issues have been identified.

It should be noted that after the completion of Chinchilla trial, the collaboration between Linc Energy and Ergo Exergy was terminated. In December 2006, Linc Energy signed two co-operation agreements with the Skochinsky Institute of Mining in Moscow, Russia, and its parent organization, the Scientific-Technical Mining Association. The Skochinsky Institute will provide consultation and engineering services to Linc Energy, including relevant UCG technology transfer and training, teaming up with senior Linc Energy engineers in the development of the UCG process at Chinchilla to produce quality syngas from Linc Energy's coal reserves.

In October 2007, Linc Energy acquired a 60% controlling interest in Yerostigaz in Uzbekistan. Yerostigaz owns the UCG site in Angren in Uzbekistan, including significant coal reserves at this site and considerable infrastructure to support the production of gas for 400 MW power plant. Yerostigaz employs over 230 people who are trained in site selection, geology, hydrology, drilling, pipe work, gas cleanup, maintenance and operation of a commercial facility. The Yerostigaz acquisition added these experienced employees to the Linc Energy team and allowed it to have effective ownership of a significant piece of the intellectual property and know-how of UCG. With the additional employees and expertise, Linc Energy plans to move forward on expanding UCG operations in several other locations around the world, including China, India, USA and Australia. Linc Energy and Vietnam Coal and Minerals Corp., Marubeni, will use UCG technology to develop 30 billon tons of bituminous coal reserves in the Song Hong (Red River) Delta for power generation.

Currently, in collaboration with Syntroleum Corporation, Linc Energy is constructing a large coal-to-liquids plant at Chinchilla site (Fig. 6). It is expected that this plant will use syngas produced from the UCG process.

Figure 6. Chinchilla site image - GTL pilot plant commissioning, May 2008 (http://www.lincenergy.com.au).

Two other Australian companies are developing commercial projects in the UCG area. Cougar Energy Ltd. has completed resource definition at its Kingaroy site, and is undertaking final site characterization prior to commencing the pilot burn for a 400MW combined cycle power project. Carbon Energy PL will demonstrate the commercial feasibility of the CRIP UCG process at Bloodwood Creek with a 100-day field trial. The facility design will be based on the experience obtained in Rocky Mountain 1 UCG trial (US), completed in 1988, with improvements that move the technology from an experimental stage to commercial reality. The trial will be performed as the first module of a commercial facility that will generate 1 PJ (petajoule) per year of syngas with a three-year module life. Each module will produce enough syngas to produce 20 MW of electricity in a combined-cycle gas-turbine power plant. At the end of the trial, the module will be held on a standby mode while surface facilities for commercial production are put in place (http://www.syngasrefiner.com/ucg).

There are a number of other UCG research projects presently underway in Australia. The Commonwealth Scientific and Industrial Research Organization (CSIRO) is preparing a practical model of UCG that can reform real-time predictions of gasifier behavior and integrate into a model-based control system, to optimize gasifier performance. Development will also focus on providing an aid to the design of UCG field layouts. Other work includes the use of CFD modeling techniques to predict the behavior of structures, walls and rubble, under various conditions. CSIRO Petroleum Resources are involved with research work connected to the ancillary processes in a low emission UCG process. The work forms part of a proposal by a commercial operator for government funding under the greenhouse gas abatement program. The proposal involves UCG for power generation with CO_2 separation and aquifer sequestration. Finally, as mentioned above (Section 2.4), researchers at the University of Queensland, in a joint effort with Dr. Blinderman of ErgoExergy, have developed numerical models for UCG processes.

2.6 South Africa

Eskom, a coal-fired utility in South Africa, has been investigating UCG at its Majuba 4,100 MW power plant (Fig. 7) since 2001. Ergo Exergy provides the technology to build and operate a UCG pilot which was ignited on January 20, 2007. The Eskom Pilot Project will be expanded in a staged manner, based on the success of the each preceding phase. The ultimate objective of the project is to fully evaluate the technology and produce a business case for co-firing of 1,200 MW of electricity at Majuba, at an anticipated cost considerably less than from current coal prices. The natural progression for UCG proceeds into Integrated Gasification Combined Cycle (UCG-IGCC), and into other unminable coal resources in South Africa. Eskom‘s preliminary estimates show that there is 45 billion tons of coal in South Africa that is presently regarded as unminable with currently available technologies, but is still suitable for UCG. This will create a new energy source for Eskom that will enable the present generating capacity of 41 GW to be increased nine fold (http://www.eskom.co.za).

Figure 7. Majuba power plant (http://www.eskom.co.za).

The project currently generates about 3,000 m^3/hr of flared gas (http://www.syngasrefiner.com/ucg). Volumes will increase to 70,000 m^3/hr early next year and be piped to the station before eventually rising to 250,000 m^3/hr. Some 3.5 million m^3/hr will be supplied to the power station at full production that is anticipated around 2012.

2.7 China

It is generally believed that China has the largest UCG program currently underway. This is confirmed by a relatively large number of patents in the UCG area, obtained by Chinese engineers (see Fig. 3). Since the late 1980s, sixteen UCG trials have been carried out or are currently operating. Chinese trials utilize abandoned galleries of disused coal mines for the gasification. Vertical boreholes are drilled into the gallery to act as the injection and production wells. Researchers at the China University of Mining and Technology investigated the two-stage UCG process proposed by Kreinin (1990) for production of hydrogen, where a system of alternating air and steam injection is used. The experiments, conducted in Woniushan Mine, Xuzhou, Jiangsu Province, prove the feasibility to use UCG for large-scale hydrogen production (Yang et al., 2008).

Figure 8. Model rig of UCG at the Chinese University of Mining & Technology (DTI, 2004).

The XinWen coal mining group in Shangdong province has six rectors with syngas used for cooking and heating (Creedy and Garner, 2004). A project in Shanxi Province uses UCG gas for the production of ammonia and hydrogen. Small-scale power production schemes using converted coal boilers or gas turbines are also under consideration, as is a 350 MW electric generating plant. Finally, Hebei Xin'ao Group is constructing a liquid fuel production facility fed by UCG. The $112 million project is a joint venture between this company and China University of Mining and Technology. The plant will produce 100,000 tons per year of methanol and generate 32.4 million kWh/year of power (http://www.syngasrefiner.com/ucg).

2.8 New Zealand

A UCG project was undertaken in 1994 in the Huntly coal reserve situated 120 km south of Auckland. Injection wells were linked to a production well using the CRIP process. The test was carried out over a 13-day period and approximately 80 tons of coal were gasified.

New Zealand is a tectonically active country which has resulted in the coal deposits being both faulted and folded and, in some cases, laid down on undulating basement topography. This geological complexity presents considerable technical challenges to the successful planning and extraction of coal. Solid Energy New Zealand Ltd. is an energy company founded on mining coal in difficult conditions and therefore has developed a wealth of knowledge, experience and IP in the area of resource identification, characterization and development for both opencast and underground mining in challenging geological environments. Solid Energy is planning to use UCG to complement currently employed mining methods, for low cost access to coal that is currently not technically or economically accessible. Solid Energy has exclusive rights to apply the Ergo Exergy's εUCG technology within New Zealand and is currently investigating the potential for the application of UCG in New Zealand (http://www.syngasrefiner.com/ucg).

2.9 India

UCG is a promising technology for India, which has vast coal resources, primarily of low grade. India looks to utilize its vast coal reserves, which are the fourth-largest reserves in the world, to reduce dependency on oil and gas imports. UCG will be used to tap India's coal reserves that are difficult to extract economically using conventional technologies. The Oil and Natural Gas Corporation Ltd. (ONGC) and the Gas Authority of India Ltd. (GAIL) are planning to carry out pilot projects using recommendations of experts from the Skochinsky Institute of Mining in Moscow and Ergo Exergy (Khadse et al., 2007). It is also reported that AE Coal Technologies India Pvt. Limited, a company belonging to the ABHIJEET GROUP of India, is implementing UCG Projects in India (http://www.syngasrefiner.com/ucg).

2.10 Japan

Japan, which has substantial coal interests outside its borders, as well as continental shelf resources, has included UCG in its future research plans for coal exploitation, and has been maintaining a low level program for many years. The University of Tokyo and coal companies have been conducting technical and economic studies of UCG on a small scale during the past decade and are considering conducting a trial in the near future. A feasibility study has been undertaken for a UCG trial and a 55 km^2 site area selected (Shimada et al., 1994). Predictions were based on analysis of field data from UCG trials in the USA. The study identified the largest cost elements as drilling and oxygen.

2.11 Comparison of alternative technologies

It appears that the main controversy in UCG is related to the methods for linking injection and production wells. As mentioned above, the old Soviet technology involves hydraulic fracturing and reverse combustion. The UK experts believe that directional drilling is more promising. They suggest that other than for low rank, shrinking coals, it is unlikely that reverse combustion is a reliable option (Creedy et al., 2001). They remind that reverse combustion and hydraulic fracturing were unsuccessful in trials in France; reverse combustion was also unsuccessful at Thulin in Belgium. This opinion contradicts that of Kreinin (2004), who argues that involvement of Russian experts and use of their specific technological methods would preclude the aforementioned failures.

The UK experts indicate (http://www.ucgp.com/key-facts/basic-description) that two different methods of UCG have evolved, and both are commercially available. The first, based on technology from the former Soviet Union, uses vertical wells and a method like reverse combustion to open up the internal pathways in the coal. The process has been tested (1999-2003) in Chinchilla, Australia, using air and water as the injected gases. The second, tested in European and American coal seams, creates dedicated inseam boreholes, using drilling and completion technology adapted from oil and gas production. It has a moveable injection point known as CRIP (controlled retraction injection point) and generally uses oxygen or enriched air for gasification.

It appears that this statement of two opposite methods is oversimplified. Kreinin (2004) shows that a new UCG technology has been developed in Russia, which takes into account the experience obtained in trials outside FSU. Specifically, the advantages of CRIP technique, developed in the US, are recognized, and the main idea of this method (the oxidizer injection point moves as coal is consumed) is recommended to be used along with the Russian approaches. It is claimed that, as compared with the original design solution for this idea, simpler methods have been proposed in Russia (Krejnin, 1992; Kazak et al., 1993). Kreinin (2004) describes various novel UCG techniques developed in Russia in 1980-1990s. They cannot be described in this brief report, but it appears that the new Russian technology does include old Soviet methods, guided drilling, and the CRIP idea. For example, in one design, the channels are created by directional drilling, then they are widened using reverse combustion, and finally, the oxidizer injection point moves along the channel. Other approaches, such as heat regeneration in the production well (Blinderman et al., 1996), a pressure-suction process with additional gas discharge wells (Krejnin and Blinderman, 1966), and a method to eliminate groundwater pollution (Krejnin and Dvornikova, 1997), are also of interest. It is claimed that the new technology significantly increases the efficiency of UCG process.

Thus, the literature analysis implies that it is incorrect to state that there are only two alternatives: either old Soviet technology, or directional drilling with CRIP. It appears that the "new UCG technology," described by Kreinin (2004) and possibly used by ErgoExergy, combines the advantages of all other methods.

3 Determination of Criteria for Site Selection

This analysis of UCG state of the art is focused on the determination of selection criteria for available coal resources in Indiana. The Indiana Geological Survey (IGS) in Bloomington, IN, has defined the criteria for underground mining (Mastalerz et al., 2004), which include technological and land-use restrictions, but some of the criteria for UCG are expected to be different. For example, the UCG process has specific requirements for the depth and thickness of coal seams that differ from those that constrain mining. Based on the criteria that have been applied at other UCG projects around the world, the information that the IGS has in its records will be used to constrain the potential locations for projects within Indiana.

3.1 Thickness of coal seam

Available information on the minimum seam thickness for UCG is contradictory. GasTech (2007) indicates that the optimal thickness should be more than 30 feet. However, that report considered coal seams of the Powder River Basin, Wyoming, which are mainly thick. On the contrary, ErgoExergy experts claim that UCG can be used at thickness as low as 0.5 m. As mentioned above, the UCG work in the FSU showed that the heating value of the produced gas decreases significantly with decreasing the coal thickness below 2 m (see Fig. 2). The literature analysis allowed us to make recommendations for selection of Indiana coals based on the coal seam thickness, and are shown in Table 1.

Table 1. Recommended seam thickness criteria for selection of Indiana coals.

Thickness	**Suitability**
> 2.0 m	high
1.5 – 2.0 m	medium
1.0 – 1.5 m	low
< 1.0 m	unacceptable

The coal seams in Indiana are mainly relatively thin (<1.5m). For this reason, thickness is recommended as the first criterion to be used in the selection process. This will significantly reduce the amount of coal that has to be further evaluated using other criteria. Of the seven major coal seams present in Indiana, only the Seelyville and Springfield Coals have a significant quantity of sufficiently thick sites (>1.5 m) to be considered for assessment of UCG potential (Mastalerz et al., 2004). Thus, the selection process will focus on these two coal beds only. In conjunction with calculating those portions of these two seams that meet the thickness screening criteria, the associated tonnages of these thick contiguous blocks of coal must be determined (see section 3.6).

3.2 Depth of coal seam

Our analysis of UCG literature shows that the depth of coal seams is not a critical parameter. The depth varied from 30 to 350 m in the FSU developments and US experiments, while much deeper coals (600-1200 m) were gasified in Western European trials. The LLNL experts indicate that the minimum depth should be 12 m (Burton et al., 2006). The Indiana Geological Survey has used 200 feet (~60 m) as the maximum depth for surface mining. Taking into account the relatively low cost of surface mining, and assuming that use of this technology will be continued, it is reasonable to expect that coals with depth in the range from 12 to 60 m have low suitability for UCG in Indiana.

Depth more than 300 m requires more complicated and expensive drilling technologies, but it also has advantages such as minimized risk of subsidence and the possibility to conduct the

UCG process at higher pressure, which increases the heating value of the produced gas. Also, deeper seams are less likely to be linked with potable aquifers, thus avoiding drinkable water contamination problems. Finally, if the product gas is to be used in gas turbines, additional compression may not be necessary. To decrease the risk of subsidence, Burton et al. (2006) recommend depth >200 m. On the other hand, they note that it is possible to avoid subsidence at lower depth if overburden rocks have high yield strength. These considerations and our conclusions are summarized in Table 2.

Table 2. Recommended seam depth criteria for selection of Indiana coals.

Depth	**Suitability**
> 200 m	high
60-200 m high yield strength of overburden rocks	medium
60-200 m low yield strength of overburden rocks	low
< 60 m	unacceptable

If potential UCG sites are found at different depths, further analysis should be made based on tradeoff between the higher cost of deeper wells and the advantages of UCG at larger depth. As mentioned above, a major advantage of using deeper coals for UCG is the higher gasification pressure, which leads to higher methane content and hence to higher heating value. The effect of pressure is just a consequence of the methanation equation:

$$CO + 3H_2 \rightarrow CH_4 + H_2O \qquad (2)$$

Since during this reaction the volume decreases, according to Le Chatelier's principle, an increase in pressure shifts the equilibrium to the right, i.e. the yield of methane increases. This can be illustrated by comparison of gases obtained by UCG at 4 bar (US) and 53 bar (Spain), where oxygen was used in both sites. The gas obtained at 4 bar contained 4.7% CH_4, 20.8% CO and 38.1% H_2, while the gas obtained at 53 atm contained 13.2% CH_4, 12.8% CO and 24.8% H_2 (the balance gases were CO_2 and H_2S). This resulted in heating values 8.73 MJ/m^3 and 10.9 MJ/m^3, respectively (Kreinin, 2004). Of course, if the intent is to produce chemicals and/or liquid fuels from the gasified coal, then maintaining high CO and H_2 content, rather than methane, is of interest. For the selected UCG sites with different depths, thermodynamic analysis can be conducted to estimate composition and heating value of the product gas, suitable for the particular application. This will allow us to make the final selection accounting for potential economic benefits of UCG in Indiana.

3.3 *Coal rank and other properties*

With the present state of knowledge, low rank, high volatile, non-caking bituminous coals are preferable. Burton et al. (2006) suggest that UCG may work better on lower ranks coals because they tend to shrink upon heating, enhancing permeability and connectivity between injection and production wells. It has also been suggested that the impurities in lower rank coals improve the kinetics of gasification by acting as catalysts for the burn process. For the coals of the same rank, the higher the heating value of coal, the higher the heating value of the UCG gas. Thus, if other characteristics are identical, coals with higher heating value are advantageous.

Indiana coals are characterized by high-volatile bituminous rank and have relatively high heating value, which makes them attractive for UCG. Although the heating value of Indiana coals is lower than that of the Appalachian Bassin, it compares favorably with western coals, for example, Powder River Basin coals (Mastalerz et al., 2004), which were evaluated recently for UCG (GasTech, 2007).

Porosity and permeability of the coal seam is also an important factor, but it is difficult to use this factor as a criterion at this point because of the scarcity of this type of data. Better cleated and more permeable seams make it easier to link the injection and production wells, and increase the rate of gasification by making reactant transport easier. On the other hand, higher porosity and permeability increase the influx of water, and increase product gas losses.

Also, it is often recommended that coals should not exhibit significant swelling upon heating. In particular, Sury et al. (2004a) state that, in general, reverse combustion works well in shallow non-swelling coal but is not recommended at great depth and in swelling coal. This contradicts, however, the opinion of Burton et al. (2006) who note that the FSU methods demonstrated minimum sensitivity to coal swelling: the large-dimension channels formed in the linkage process are not likely to be plugged by coal swelling. Areas of seams that are free of major faulting in the vicinity (<45 m) of the proposed gasifier, and which could potentially provide a pathway for water inflow or gas migration, should be preferentially targeted (Sury et al., 2004b).

3.4 *Dip of coal seam*

Sury et al. (2004b) indicate that shallow dipping seams are preferable. Such seams facilitate drainage and the maintenance of hydrostatic balance within the gasifier, and minimize potential damage to the down dip production well from strata movements associated with UCG. The report by GasTech (2007) recommends angles 0-20 degrees and Indiana coals place within this range. However, UCG has been successfully carried out in steeply dipping seams, thus dip is not an important criterion for selecting UCG sites.

3.5 *Groundwater*

Water is an essential component of UCG process, and thus its presence within a coal seam and near it is an important characteristic. The neighboring rocks should contain saline formations (non-potable aquifers). One may think that it is desirable to have a lot of water near the coal seam to provide sufficient water supply to the UCG reactor zone. The UCG experience shows, however, that usually the problem is that there is too much water (in both the coal itself and near the seam), which leads to lower heating value of the produced gas (see Fig. 2). Thus, it is desirable to select coals with relatively low moisture content, located far from abundant water reserves. Often, drying is recommended as preparation to UCG.

Sury et al. (2004b) recommend using coal seams with no overlying aquifers within a distance of 25 times the seam height. Trials have been successfully carried out in seams in closer proximity to aquifers, but the potential risk of contamination is increased.

3.6 Amount of coal

Gas produced by the underground gasification process can potentially be used in a series of applications. These applications range from supplying mobile units that could provide gas in agricultural areas to large power and chemical plants producing hundreds and thousands MW of electrical energy and vast amounts of hydrocarbon-based products. For this reason, the evaluation of potentially productive sites must include the determination of the amount of coal available for gasification in conjunction with consideration of potential applications. Additionally, for each potential site, the productive lifetime of the site must be determined as a function of required gas yield. For illustration, a 300-400 MW UCG-based power plant requires gasification of 250-350 thousand tons of standard coal per year (Kreinin, 2004), i.e. 5-7 million tons of standard coal are required for 20-year operation period of such a plant.

The volumes of coal available for gasification will be determined by the IGS in Phase 2 of this assessment. Tonnages of coal present in each contiguous block will be calculated for the two beds assessed.

3.7 Land-use restrictions

There is no indication in the literature that UCG should be further from towns, roads and other objects than underground mines, assuming that the process design and environmental monitoring ensure ecological safety. Thus, the land-use restrictions for underground mining determined by IGS (Mastalerz et al., 2004) can be applied to potential UCG sites.

3.8 Noise

Site selection, particularly proximity to residential dwellings, would determine the noise impact of a UCG site. The cumulative effects of noise levels resulting from UCG operations are not expected to be noticeable to residents or visitors within the area except during construction activities or around compressor facilities.

4 Summary and Recommendations

The conducted analysis of UCG current status shows that this is a mature technology, which has a great potential to grow and replace/complement traditional methods for coal mining and gasification. New commercial UCG projects have started recently in several countries and more projects will probably start soon. Many of them use techniques and approaches developed in the former Soviet Union and later in Russia, as well as in the United States, primarily through involvement of experts from either ErgoExergy or Russian organizations, who have expertise in commercial UCG developments. Selection of the best UCG technology is a complex process, and the properties of the UCG site must be taken into consideration.

The criteria for selecting UCG sites in Indiana have been formulated in this report. Based on the available information on the characteristics of coal seams in Indiana, it is recommended to focus on the Seelyville and Springfield Coal Members. Taking into account both UCG experience and geological characteristics of Indiana coals, the thickness of coal seam is recommended to be used as the first criterion. After determination of sites with different thickness-based suitability, depth and other criteria will be considered. After selection of potential UCG sites, additional analysis will be required, which may include thermodynamic calculations to estimate composition and heating value of the product gas for different depths and other conditions, as well as estimates of availability for specific applications. Ultimately, an economic analysis, including capital, operational and environmental costs, will need to be conducted; this, however, is beyond the scope of the current project.

5 References

Antonova, R.I., Bezhanishvili, A.E., and Blinderman, M.S. (1990) *Underground Coal Gasification in the USSR*, TsNIEIugol, Moscow.

Arens, V.Zh., Vertman, A.A., and Khcheyan, G.Kh. (2007) The Advance in Utilization of No Demanded Reserves of Minerals, *Vestnik Rossiyskoy Academii Estestvennykh Nauk. Geologia*, Vol. 3, pp. 3-6.

Blinderman, M.S., and Friedmann, S.J. (2006) *Underground Coal Gasification and Carbon Capture and Storage: Technologies and Synergies for Low-Cost, Low-Carbon Syngas and Secure Storage*, Report No. UCRL-ABS-218560, Lawrence Livermore National Laboratory, Livermore, CA.

Blinderman, M.S., and Jones, R.M. (2002) The Chinchilla IGCC Project to Date: UCG and Environment, 2002 Gasification Technologies Conference, San Francisco, CA.

Blinderman M.S., Kapralov, V.K., and Krejnin, E.V. (1996) Heat-Recovery Hole, Patent 2055174.

Blinderman, M.S., and Klimenko, A.Y. (2007) Theory of Reverse Combustion Linking, *Combustion and Flame*, Vol. 150, pp. 232-245.

Blinderman, M.S., Saulov, D.N., and Klimenko, A.Y. (2008a) Exergy Optimisation of Reverse Combustion Linking in Underground Coal Gasification, *Journal of the Energy Institute*, Vol. 81, pp. 7-13.

Blinderman, M.S., Saulov, D.N., and Klimenko, A.Y. (2008b) Forward and Reverse Combustion Linking in Underground Coal Gasification, *Energy*, Vol. 33, pp. 446-454.

Britten, J.A., and Thorsness, C.B. (1989) *CAVSIM Underground Coal Gasification Program*, Report No. ESTSC-000773IBMPC00, Lawrence Livermore National Laboratory, Livermore, CA.

Burton, E., Friedmann, J., and Upadhye, R. (2006) *Best Practices in Underground Coal Gasification*, Contract No. W-7405-Eng-48, Lawrence Livermore National Laboratory, Livermore, CA.

Chandelle, V. Fabry, R., Kurth, M., Li, T.K., Patigny, J., and Sonntag, C. (1986) Overview about Thulin Field Test, Proceedings of the Twelfth Annual Underground Coal Gasification Symposium, Saarbrucken, Germany, pp. 53-59 (DOE/FE/60922-H1).

Creedy, D.P., and Garner, K. (2004) *Clean Energy from Underground Coal Gasification in China*, DTI Cleaner Coal Technology Transfer Programme, Report No. COAL R250 DTI/Pub URN 03/1611, DTI, UK.

Creedy, D.P., Garner, K., Holloway, S., Jones, N., and Ren, T.X. (2001) *Review of Underground Coal Gasification Technological Advancements*, Report No. COAL R211, DTI/Pub URN 01/1041, DTI, UK.

Den'gina, N.I., Kazak, V.N., and Pristash, V.V. (1994) Changes in Rocks at High Temperatures. *Journal of Mining Science*; Vol. 29, pp. 472-477.

DTI (2004) *Review of the Feasibility of Underground Coal Gasification in the UK*, Cleaner Fossil Fuels Programme, DTI/Pub URN 04/1643, DTI, UK.

Gadelle, A., Pavone, D., Raffoux, J., and Ternot, A. (1985) Status of French UCG Field Test at La Haute Deule, Proceedings of the 11th Annual Underground Coal Gasification Symposium, Denver, CO, pp. 92-106 (DOE/METC-85/6028, DE85013720).

GastTech (2007) *Viability of Underground Coal Gasification in the "Deep Coals" of the Powder River Basin, Wyoming*, Prepared for the Wyoming Business Council Business and Industry Division State Energy Office, Casper, WY.

Gregg, D.W., and Edgar T.F. (1978) Underground Coal Gasification, *AIChE Journal*, Vol. 24, pp. 753-781.

Hill, R. W. (1986) Review of the CRIP Process, Proceedings of the 12th Annual Underground Coal Gasification Symposium, Saarbrucken, Germany (DOE/FE/60922-H1).

Kazak, V.N., Kapralov, V.K., and Krejnin E.V. (1993) Method for Putting on Blast into Coal Seam in Underground Gasification, Patent RU2004785.

Khadse, A., Qayyumi, M., Mahajani, S., and Aghalayam, P. (2007) Underground Coal Gasification: A New Clean Coal Utilization Technique for India, *Energy*, Vol. 32, pp. 2061-2071.

Kolokolov, O.V., and Tabachenko, N.M. (1992) Ecologically Sound Technologies of Mining, Preparation and Use of Coal. *Ugol*, pp. 40-42.

Kreinin, E.V. (1990) Two-stage In-situ Coal Gasification. *Khimiya Tverdogo Topliva*, Vol. 6, pp. 76-79.

Kreinin, E.V. (2004) *Nontraditional Thermal Technologies for Production of Heavy-Extractable Fuels: Coal, Hydrocarbons*, OAO Gazprom, Moscow.

Kreinin, E.V., and Dvornikova, E.V. (1993) Does In-Situ Gasification of Coal Seams Cause Pollution of Underground Water? *Ugol*, Vol. 4, pp. 39-40.

Kreinin, E.V., Fedorov, N.A., Zvyagintsev, K.N., and Pyankova, T.M. (1982) *Underground Gasification of Coal Seams*, Nedra, Moscow.

Kreinin, E.V., and Shifrin, E.I. (1993) Mathematical model of coal combustion and gasification in a passage of an underground gas generator. *Combustion, Explosion, and Shock Waves*, Vol. 29, pp. 148-154.

Krejnin, E.V. (1992) Method of Underground Gasification of Combustible Minerals, Patent SU1716110.

Krejnin, E.V., and Blinderman, M.S. (1996) Method for Pressure-Suction Underground Gasification of Coal, Patent RU2066748.

Krejnin, E.V., and Dvornikova, E.V. (1997) Method of Underground Gasification of Coal, Patent RU 2090750.

Kurth, M., Depouhon, F., Patigny, J., and Ledent, P. (1986) Linking and Gasification in Thulin, A New Endeavor, Proceedings of the 12th Annual Underground Coal Gasification Symposium, Saarbrucken, Germany, pp. 60-65 (DOE/FE/60922-H1).

Lazarenko, S.N., and Kreinin, E.V. (1994) *Underground Coal Gasification in Kuzbass: Present and Future*, Institute of Coal, Siberian Branch of the Russian Academy of Sciences, Nauka, Novosibirsk (ISBN 5-02030792-0).

Lazarenko, S.N., and Kreinin, E.V. (2006) *Underground Coal Gasification in Kuzbass: New Opportunities*, Institute of Coal and Geochemistry, Siberian Branch of the Russian Academy of Sciences, Kemerovo (ISBN 5-90230525-X).

Mastalerz, M., Drobniak, A., Rupp, J., and Shaffer, N. (2004) *Characterization of Indiana's Coal Resource: Availability of the Reserves, Physical and Chemical Properties of the Coal, and the Present and Potential Uses*, Final Report to the Center for Coal Technology Research, Indiana Geological Survey Open-File Study 04-02, Bloomington, IN.

Pirard, J.P., Brasseur, A., Coëme, A., Mostade, M., and Pirlot, P. (2000) Results of the Tracer Tests during the El Tremedal Underground Coal Gasification at Great Depth, *Fuel*, Vol. 79, pp. 471-478.

Shimada, S., Tarmari, A., Ishii, E. (1994) Feasibility Study on Underground Coal Gasification in Japan, *Shigen to Sozai*, Vol. 110, Part 3, pp. 64-68.

Sury, M., White, M., Kirton, J., Carr, P., Woodbridge, R., Mostade, M., Chappell, R., Hartwell, D., Hunt, D., and Rendell N. (2004a) *Review of Environmental Issues of Underground Coal Gasification*, Report No. COAL R272, DTI/Pub URN 04/1880, DTI, UK.

Sury, M., White, M., Kirton, J., Carr, P., Woodbridge, R., Mostade, M., Chappell, R., Hartwell, D., Hunt, D., and Rendell N. (2004b) *Review of Environmental Issues of Underground Coal Gasification – Best Practice Guide,* Report No. COAL R273, DTI/Pub URN 04/1881, DTI, UK.

Yang, L., Zhang, X., Liu, S., Yu, L., and Zhang, W. (2008) Field Test of Large-scale Hydrogen Manufacturing from Underground Coal Gasification (UCG), *International Journal of Hydrogen Energy*, Vol. 33, pp. 1275-1285.