Underground Coal Gasification: A Brief Review of Current Status

Evgeny Shafirovich[†] **and Arvind Varma***

School of Chemical Engineering, Purdue University, 480 Stadium Mall Drive, West Lafayette, Indiana 47907

Coal gasification is a promising option for the future use of coal. Similarly to gasification in industrial reactors, underground coal gasification (UCG) produces syngas, which can be used for power generation or for the production of liquid hydrocarbon fuels and other valuable chemical products. As compared with conventional mining and surface gasification, UCG promises lower capital/operating costs and also has other advantages, such as no human labor underground. In addition, UCG has the potential to be linked with carbon capture and sequestration. The increasing demand for energy, depletion of oil and gas resources, and threat of global climate change lead to growing interest in UCG throughout the world. In this article, we review the current status of this technology, focusing on recent developments in various countries.

1. Introduction

Coal is an abundant source for energy and chemicals in many parts of the world. As proven oil reserves are depleted, coal is expected to play an increasingly important role, at least until economical renewable energy sources are developed. In this context, gasification is considered to be a promising option for the future use of coal. The coal gasification process produces syngas (a mixture of CO, H_2, and other constituents), which can be used for the generation of electricity or for the production of liquid hydrocarbon fuels, natural gas surrogates, and 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. It is expected that carbon sequestration will become a commercial technology, mandatory in newly constructed power plants.

Coal gasification generally requires construction of special plants, including large coal storage facilities and gasifiers. Meanwhile, there exists an alternative method, denoted underground coal gasification (UCG), in which injection and production wells are drilled from the surface and linked together in a coal seam. Once the wells are linked, air or oxygen is injected, and the coal is ignited in a controlled manner. Water present in the coal seam or in the surrounding rocks flows into the cavity formed by the combustion and is utilized in the gasification process. The produced gases (primarily H_2, CO, CH_4, and CO_2) flow to the Earth's surface through one or more production wells. After being cleaned, these gases can be used to generate electric power or synthesize chemicals (e.g., ammonia, methanol, and liquid hydrocarbon fuels).

The UCG process has several 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 or capital for underground coal mining, minimum surface disruption, no coal transportation costs, and direct use of water and feedstock available in situ. In addition, cavities formed as a result of UCG could potentially be used for CO_2 sequestration.

The UCG process, however, also has areas of potential improvement and customization to local conditions that must be addressed through additional research and development. These improvements must advance the effectiveness of the gasification process while minimizing any potential detrimental effects on the setting. Some of the domains where improvements could optimize the process include the linking of injection and production wells within a coal seam, minimization of variation in the composition of the produced gas, and prevention of any degradation of potable groundwater supplies.

UCG research and development have been conducted in several countries, including long-term commercial operation of several UCG plants in the former Soviet Union. Information on UCG technology, however, is limited, and despite the availability of recent reports[1−7] and monographs,[8−10] there is a lack of compact review articles in this area. Further, books[8−10] on this topic have been written in Russian, making them difficult for anyone unfamiliar with the language. We have recently reviewed the current status of UCG throughout the world and analyzed the criteria for selecting UCG locations. This article presents the main results of this work.

2. Analysis of the Current State of UCG Science and Technology

2.1. USSR (before 1991); Russia, Ukraine, and Uzbekistan (after 1991). In the former Soviet Union (FSU), an intensive research and development (R&D) program on UCG was conducted from the 1930s, leading to the operation of several industrial-scale UCG plants. In the 1960s, five UCG gas production stations were operating, and as many as 3000 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 in 1996.[8] The only remaining commercial UCG site in the independent states formed after the collapse of the FSU is located in Angren, Uzbekistan. It is generally believed that UCG in the FSU declined in the 1970s as a result of the discovery of extensive natural gas resources in Siberia. Yet, over 15 Mt of coal have been gasified underground in the FSU, generating 50 Gm^3 of gas. For comparison, only 50 and 35 Kt of coal have been gasified in the United States and Australia, respectively.

Gregg and Edgar[11] have provided a comprehensive review of UCG R&D in the USSR from the 1930s to the 1970s. Later,

---

* To whom correspondence should be addressed. Tel.: 765-494-4075. Fax: 765-494-0805. E-mail: avarma@purdue.edu.

[†] Current address: The University of Texas at El Paso, Mechanical Engineering Department, El Paso, TX 79968. E-mail: eshafirovich2@utep.edu.

10.1021/ie801569r CCC: $40.75

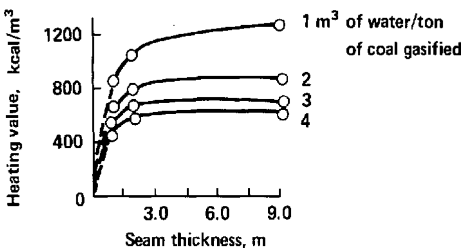

Figure 1. Effect of seam thickness and the specific water inflow into gasification zones on the heating value of gas obtained by UCG.[11]

detailed reviews were published in the Russian language.[9,12,13] Recent monographs[8,9] also review old Soviet UCG activity and, in addition, include information on recent work in Russia.

In particular, one problem of UCG technology is the necessity to link the injection and production wells within the coal seam. In many cases, the coal seam has low permeability, and a linkage technology is necessary. After testing different methods for linking the injection and production wells, relatively inexpensive technologies were developed in the FSU, such as hydraulic fracturing of the coal seam by pressurized air (or water) (this technology is common in the oil and gas industry) and so-called reverse combustion linking (ignition near the production well and counter-current flame propagation toward the injection well). It should be noted that directional in-seam drilling has been successfully competing with these technologies for many decades. Nevertheless, hydraulic fracturing and reverse combustion linking remain attractive because of their relatively low costs, and they can be used either alone or in combination with drilling.

The results of UCG R&D in the FSU are important for the selection of UCG sites. For example, it was shown[8] that the UCG process based on injecting air produces fuel gas with a heating value limited to 4.6−5.0 MJ/m^3, typically 3.3−4.2 MJ/m^3. Long-distance transportation of this gas decreases the economic effectiveness; thus, the best approach is to use it (for power generation or for conversion to other products) near the UCG site. 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 a UCG station in Lisichansk (Donetsk Basin, Ukraine) where cheap oxygen was available as a byproduct of inert gas production.[8] Use of steam and O_2 injection can increase the heating value of the fuel gas to 10−12 MJ/m^3. Although the use of oxygen increases the costs, the technique remains economically feasible. A careful cost/benefit analysis is required to evaluate different options, such as constructing a power plant vs transporting the gas long distance and using oxygen instead of air.

Another important result is related to the coal seam thickness. It was shown that a decrease in the seam thickness can reduce the heating value of the produced gas, which is associated with heat loss to the surrounding formation. For example, for one particular UCG plant, the gas heating value decreased significantly as the seam thickness fell below 2 m (Figure 1).

As mentioned above (section 1), the UCG process usually consumes water contained in the coal seam and adjacent strata. Also, water can be pumped as steam, along with air or oxygen, into the injection well. In any case, some amount of water will remain unreacted, which potentially can lead to contamination of groundwater by harmful byproducts of the UCG process. To avoid this, environmental monitoring during and after the UCG process needs to be conducted. The results of environmental monitoring in the FSU can be illustrated by the example of the Yuzhno−Abinsk Podzemgaz station in the Kuznetsk Basin, where increases in the phenol concentration in the groundwater were observed, but it was concluded that water contamination during UCG was of a local nature and at admissible concentrations of harmful compounds. Specifically, the phenol concentration in water samples from the UCG cavity achieved a maximum of 0.017 mg/L, but in the surrounding area, water sampled from 18 monitoring boreholes contained only 0.0007−0.0042 mg/L phenol.[14] In three months after the completion of gasification operations, the phenol concentration in water samples from the cavity was lower than the maximum allowable concentration of phenol in drinking water, 0.001 mg/L.[8] In addition, it was shown experimentally that coals are highly effective in removing phenols, thus ensuring self-purification of contaminated groundwater.[15] Note, however, that phenol is not a good indicator of contamination, as it is water-soluble and, hence, can be washed away by regional groundwater flow. In contrast, compounds such as benzene, ethylbenzene, toluene, and xylenes (BETX) and polycyclic aromatic hydrocarbons (PAHs) are not soluble and are more significant indicators of environmental performance. The monitoring of BETX, PAHs, and phenolic compounds along with inorganic contaminants has been prominent in recent UCG projects in Australia and South Africa,[16] and it will be required in future UCG projects.

Research and development of underground gasification technology have been conducted in the FSU using mathematical modeling to simulate gasification processes and products. A steady-state model was developed for coal gasification in a long channel with a constant cross section, where air and water flow into the channel and react with the coal.[17] This model involves heterogeneous chemical reactions

$$C + O_2 \rightarrow CO_2 \tag{2}$$

$$2C + O_2 \rightarrow 2CO \tag{3}$$

$$C + CO_2 \rightarrow 2CO \tag{4}$$

$$C + H_2O \rightarrow CO + H_2 \tag{5}$$

$$C + 2H_2O \rightarrow CO_2 + 2H_2 \tag{6}$$

$$C + 2H_2 \rightarrow CH_4 \tag{7}$$

and reactions in the gas phase

$$2CO + O_2 \rightarrow 2CO_2 \tag{8}$$

$$2H_2 + O_2 \rightarrow 2H_2O \tag{9}$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{10}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{11}$$

$$CO + 3H_2O \rightarrow CH_4 + H_2O \tag{12}$$

It is assumed that the flow is turbulent and that the gas is radially well mixed (no gradients over the channel cross section). The model includes balance equations for gas species (O_2, CO_2, CO, H_2O, H_2, CH_4, and N_2), momentum, and energy, as well as a thermal conduction equation for the coal. Kinetic parameters for the involved reactions are taken from the literature. Gas compositions and temperatures along the channel axis can be calculated for various parameters, such as the entrance pressure, air flow rate, and water-to-coal ratio. In the published example, the channel cross section (area = 1 m^2) was an isosceles triangle with the legs as the coal walls and the base as the inert wall. The calculations were made for an air flow rate of 5000 m^3/h and pressure at the channel entrance of 200 kPa. Figure 2 shows the calculated concentrations of the gas species (O_2, CO_2, CO, H_2, and CH_4) and the temperatures of coal (T_c) and gas (T_g) as functions of the channel length, x, at 1 m^3 water vapor per ton

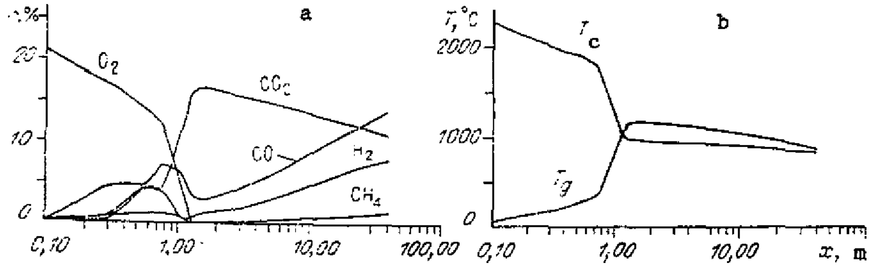

Figure 2. Calculated (a) concentrations of the species O_2, CO_2, CO, H_2, and CH_4 and (b) temperatures of coal (T_c), and gas (T_g) as functions of the channel length, x.[17]

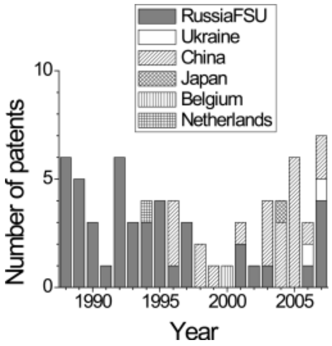

Figure 3. Number of patents in the UCG area for the period from 1988 through 2007, where the year indicates the year of patent publication. Country indicates where the inventors worked (where RussiaFSU means the former Soviet Union and, after its collapse, Russia).

of reacted coal. The profiles include three zones: (1) In the low-temperature oxidation zone ($x < 0.6$ m), the concentration of O_2 decreases, and the concentrations of all other species increase. (2) In the high-temperature oxidation zone ($0.6 < x < 1.0$ m), the concentration of CO_2 sharply increases, and the concentrations of all other species decrease. (3) In the gasification zone ($1 < x < 40$ m), the concentrations of CO, H_2, and CH_4 gradually increase, whereas the concentration of CO_2 decreases.

The obtained results demonstrate that the model adequately describes some important features of the UCG process and, according to the authors, correlates well with experiments. However, features such as coal pyrolysis and cavity growth are beyond the scope of this model.

Other research has assessed the effects of UCG on the strata that immediately adjoin the coal seam. The results indicate that the pattern of roof deformation due to the UCG process and the filling of cavities with caved rocks is intimately linked with the physical, mechanical, and thermal properties of the rocks. At temperatures of 1000−1400 °C, rocks can deform, swell, and expand.[18]

Models for the interaction of gaseous products with groundwater have also been developed. Based on the monitoring data, a filtration−migration model for the prediction of pollution migration from a pollution source to groundwater was developed.[19]

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 numbers of patents in the UCG field issued in different countries from 1988 through 2007. This analysis was conducted using the database of the European Patent Office.[20] Information from the database of the World Intellectual Property Organization (WIPO)[21] produced identical results. It can be 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. A search conducted in February 2009 for patent applications published in 2008 showed five patents granted to researchers in China, three in Russia, one in Ukraine, and one in the United States.

2.2. United States. Initial UCG tests in the U.S. were conducted in Alabama in the 1940−1950s. Later, the UCG program was renewed, and more than 30 experiments were conducted between 1972 and 1989 under various mining and geological conditions at various localities in the country, including four in Wyoming, four in Texas, one in Washington, and one in Virginia.[1] Most of these were part of the U.S. Department of Energy's coal gasification program, although some were funded by industry. The experiments included various diagnostics and subsequent environmental monitoring. A brief review of these trials has been provided by GasTech Inc.[5]

An important result of prior UCG work in the U.S. is the development of the Controlled Retracting Injection Point (CRIP) process by researchers of the Lawrence Livermore National Laboratory (LLNL).[1,22] In the CRIP process, a production well is drilled vertically, and an injection well is drilled using directional drilling techniques to connect it to the production well (see Figure 4). Once the connection, or 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 linear or 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 deteriorating 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 linear), and a new gasification cavity is initiated. In this manner, precise control over the progress of gasification is obtained.

The CRIP technique and clean-cavern concept were used in the Rocky Mountain 1 trial, which is considered to be the most successful UCG test in the U.S. This trial was conducted from November 1987 to February 1988 in Carbon County, Wyoming. Oxygen and steam were injected into a sub-bituminous coal seam (thickness, 10 m; depth, 130 m). Along with CRIP, another linking technology, the so-called extended linked well (ELW), was tested. The ELW test lasted 57 days, consuming 4443 t of coal and producing an average heating value of 9.7 MJ/m^3. The CRIP trial lasted a total of 93 days and gasified 11227 t of coal with average gas heating values of 10.7 MJ/m^3. It should be noted that pressure in the UCG cavity was maintained below hydrostatic to minimize the loss of organic laden gases and to ensure a small but continuous influx of groundwater into the gasification cavity. As a result, the environmental impact of UCG was found to be minimal.[5]

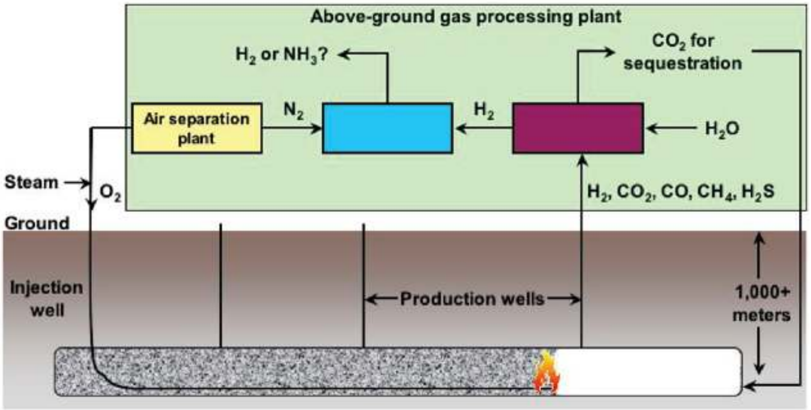

Figure 4. Schematic of the CRIP process.[1]

In parallel to the trials, a number of mathematical models for UCG have also been developed in the U.S. A brief review of UCG models developed through the end of 1970s was provided by Gregg and Edgar.[11] Among later developments, analytical[23,24] and numerical[25] models should be mentioned. Britten and Krantz[23,24] applied the method of activation energy asymptotics to analyze the dynamics of a planar combustion wave traveling in a porous medium in a direction opposed to the forced oxidant flux, similar to reverse combustion linking. The model assumes an infinite effective Lewis number and one-step, first-order Arrhenius kinetics for this two-phase, oxygen-limited combustion process. The fuel is modeled as a single-component gas-phase species devolatilized from the medium ahead of the combustion zone. The obtained values of steady front velocity and front temperature agree well with results of numerical calculations. The analysis also determines conditions for the extinction of the steady reverse combustion front in terms of the heat loss strength and oxidant flux and shows the existence of two solutions for heat losses below the extinction value. The predicted dependences of the steady front velocity and temperature on the heat loss intensity agree qualitatively with experimental observations.

Britten and Thorsness[25] have developed a model describing cavity growth and gas production during UCG in thick (∼10-m) coal layers. It is applicable to the UCG of shrinking coals in which oxidant injection is maintained at a fixed point low in the coal seam. The model is based on a few fundamental assumptions, namely, that the cavity is axisymmetric about the injection point, all resistance to injected gas flow is through ash and overburden rubble that accumulates on the cavity floor, thermal radiation dominates in the well-mixed void space, and the coal and overburden spall or rubble on a small scale as a result of parametrized thermal effects. A unified model integrates results of separate but interacting submodels that describe key phenomena occurring at different locations in and around the UCG reactor, as shown in Figure 5. These submodels quantify water influx from the coal aquifer; flow dispersion through a rubble bed at the bottom of the cavity; thermal degradation and chemical attack of rubble-covered coal sidewalls contacted by the injected reactants; and recession of cavity surfaces enclosing a void space in the upper cavity, caused by small-scale fragmentation and gasification driven primarily by radiative heat transfer. The model predicts recession rates of cavity surfaces and generation rates of major product species that compare well with experimental data from two UCG field tests. For example, Figure 6 shows H_2 and CO production rates in the first two CRIP reactors during the Rocky Mountain I UCG field test. It can be seen that the model predictions are in accord with the measurements. The drop in flows around day 53 is due to purposely lowered injection flows immediately before and after the CRIP pipe-cutting maneuver that initiated the second reactor. Note, however, that the Rocky Mountain I field tests were conducted in a thick (7.6-m) seam and the model might not be applicable for thinner seams (discussed later in section 2.3).

The research in the U.S. has highlighted the importance of assessing the geological and hydrogeological settings for UCG. A recent investigation at LLNL was focused on geomechanical processes in coal and surrounding rocks during UCG.[26] A suite

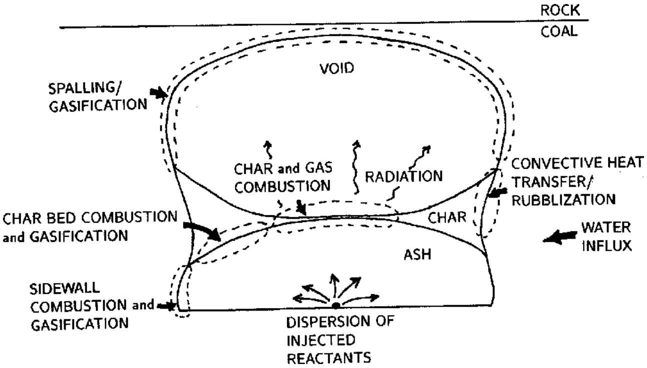

Figure 5. Schematic of the UCG cavity and occurring processes.[25]

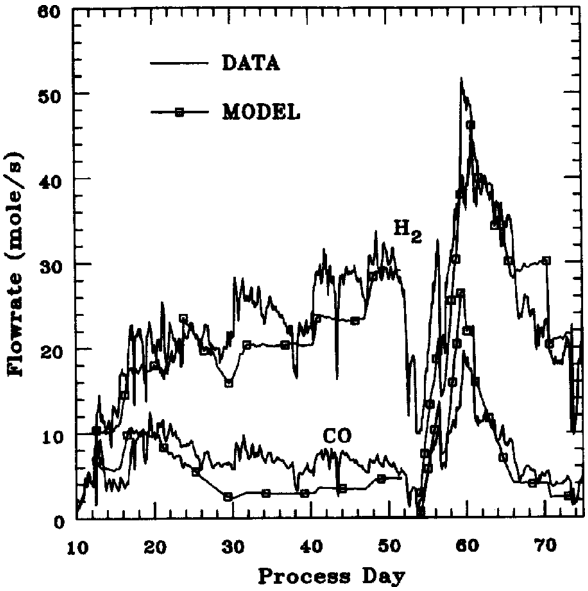

Figure 6. Model predictions of H_2 and CO production rates compared with field data.[25]

of highly nonlinear computational tools in both two and three dimensions was applied to a series of UCG scenarios. The simulations included combinations of continuum and discrete mechanical responses by employing fully coupled finite-element and discrete-element capabilities.

After the decline of oil and gas prices in the early 1980s, large-scale UCG projects were not conducted in the U.S. In recent years, because of growing energy needs, interest in UCG has been rejuvenated. BP and GasTech Inc. are developing a 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 a technical cooperation agreement on UCG. The initial two-year technical agreement addresses 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 pilot-test results and match them with historical data. 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.[27]

The issue of carbon management during the UCG process is an important aspect of UCG development in the U.S.[1,28] It is noted that all three main approaches to CO_2 capture in surface power plants (precombustion, postcombustion, 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, because of reduced costs for drilling, etc.), but there are limitations and problems that require further investigation.[29] Note that the cavity should be located deeper than 800 m, so that CO_2 can be stored in the supercritical state, allowing significantly higher utilization of the pore space available. The potential risks include sudden phase changes during CO_2 injection, adverse geomechanical and geochemical responses, groundwater displacement, and CO_2 leakage.[1]

2.3. European Union. 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 the FSU and U.S.).

In France, the first trial was conducted[30] at Bruay en Artois (coal seam thickness, 1.2 m; depth, 1170 m) in 1980−1981. Two technological and five monitoring wells were drilled. The distance between the injection and production wells was 65 m. Hydraulic fracturing (pressure, 50.7 MPa) did not lead to a satisfactory link between the wells. Attempts to use reverse combustion linking also failed because of coal self-ignition near the injection well. The main reason for the failure of this experiment was apparently a poor hydraulic connection between the wells, which led to the need for high pressure in the reverse combustion procedure and, as a result, to the coal self-ignition. The second trial was conducted[31] at La Haute Deule (coal seam thickness, 1.8 m; depth, 880 m) in 1983. Two vertical wells were drilled (distance, 60 m). The hydraulic fracturing and reverse combustion linking were again unsuccessful. In both trials, gasification of the coal seam was not achieved.

In the framework of a joint Belgium−Germany project, UCG trials were conducted near Thulin, Belgium.[32−34] In 1982, four wells were drilled, and an attempt to link them by reverse combustion was unsuccessful. A new attempt in 1984 also failed. Subsequent attempts to gasify coal resulted in the production of small portions of gas with different compositions, but hydraulic resistance between the wells remained large, indicating that the wells were not linked properly.

In the 1990s, a UCG project of the European Union was conducted by Spain, the U.K., and Belgium at El Tremedal in the Province of Teruel, Spain, which was chosen based on its geological suitability, coal seam depth (550 m), and extensive set of available borehole data.[35,36] 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 injection well, obtained by directional drilling, had vertical and horizontal parts as in the CRIP technique (see Figure 4). Three attempts to create the UCG process using oxygen were undertaken. During the experiments, continuous pressure monitoring was conducted, and pressure was maintained close to the hydrostatic value at the coal seam depth (5.3 MPa). The first attempt lasted 9 days and resulted in the production of a gas mixture containing 24.9% H_2, 8.7% CO, 14.3% CH_4, 43.4% CO_2, and 8.3% H_2S, with a heating value 10.97 MJ/m^3. The second test lasted 3 days and produced a similar gas composition of 24.7% H_2, 15.6% CO, 12.4% CH_4, 39.4% CO_2, and 8.8% H_2S, with a heating value 10.9 MJ/m^3. During the third test, technical problems, such as a malfunction of the ignition system and a failure of the temperature measurement system, resulted in the accumulation of methane and a subsequent explosion. The injection well was damaged, and the decision was made to terminate the trial.

It should be noted that the high gas pressure used in the European trials led to higher concentrations of methane in the product gas.[35] This can be illustrated by comparison with the results of the UCG trial at 0.4 MPa (U.S.), where oxygen was also used. The gas obtained at 0.4 MPa contained 38.1% H_2, 20.8% CO, 4.7% CH_4, 34.9% CO_2, and 1.5% H_2S. The effect of pressure is simply a consequence of the methanation reaction (eq 12). Because the volume decreases during this reaction, according to Le Chatelier's principle, an increase in pressure shifts the equilibrium to the right, so that the yield of methane increases.

In the 1990s, in addition to experiments, numerical models of the cavity growth in thin coal seams were developed in Belgium[37−39] and The Netherlands.[40−42] For UCG in thin (<2 m) European seams, the permeable-packed-bed concept used by Britten and Thorsness[25] (see section 2.2) is applicable only during the initial stages of the gasification process. The researchers in Europe have developed channel-gasification models, based on a simplified description proposed by Wilks[43] and postulated two zones in the UCG gasifier: a low-permeability zone of rubble/ash around the injection well and a high-permeability, narrow, peripheral zone near the coal wall (Figure 7). The Belgian group developed a two-dimensional model for UCG cavity growth in thin seams.[39] The model combines laminar flow through a porous medium around the injection point with the calculation of chemical processes in the peripheral zone adjacent to the coal wall. Figure 8 shows the calculated cavity shape and stream lines around the injection point. The bottom image corresponds to the situation where the low-permeability zone reaches the production well. This criterion can be used to define the end of the gasification process.

The Dutch group developed a two-dimensional, quasi-steady-state model of a laterally extending, partially collapsing gasification channel.[40] The model includes the chemistry of coal gasification, diffusional transport phenomena, pyrolysis of coal, and radiant heat exchange within the channel and with spalling cap rock. The quasi-steady-state approach leads to relatively simple model equations in which only one single cross-sectional

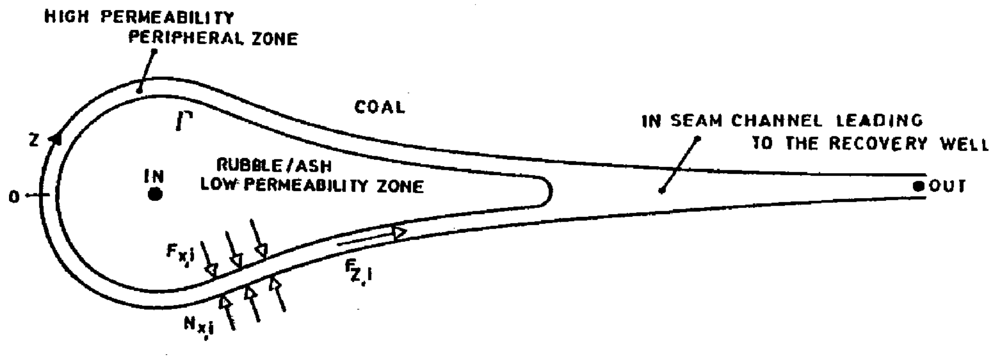

Figure 7. Schematic of a UCG reactor in thin seams.[39]

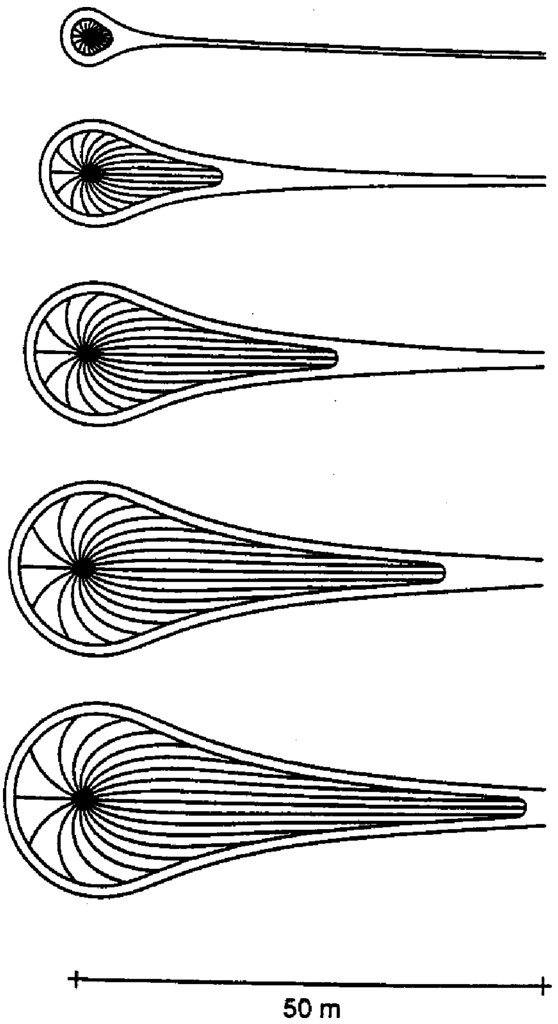

Figure 8. Cavity shape and stream lines after 0, 5, 10, 15, and 18 days of gasifier development,[39] for a 50-m distance between injection and production wells.

element of the channel needs to be considered. The model was used to demonstrate the influence of operating conditions such as pressure, air injection rate, and water injection rate on the product gas composition. A comparison between observations from the UCG field test (seam thickness, 2 m) in Pricetown, West Virginia, and model predictions showed similar gas composition and process temperatures.

Later, the Dutch group developed a more comprehensive model[41,42] for studying the transport phenomena in UCG cavities based on a finite volume discretization of the Navier–Stokes equations and the $k-\varepsilon$ turbulence model. Depending on the operating conditions, the fluid flow was dominated by either buoyancy due to temperature or concentration gradients. The predicted composition and heating value of the product gas were in good agreement with both the experimental data from the Pricetown field test and the results of simplified model.[40]

In the U.K., the Department of Trade and Industry Technology (DTI) identified UCG as one of the potential future technologies for the development of the U.K.'s large coal reserves.[4] An initial prefeasibility 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.[6,7] provided a detailed analysis of the environmental aspects of UCG.

Currently, the Hydrogen Oriented Underground Coal Gasification for Europe (HUGE) project is being conducted by research organizations in Poland and several other countries of the European Union.[44] Major attention in this project is paid to the integration of gasification processes with heat- and mass-transfer phenomena occurring in geological multiphase systems of complex geometry. Valuable expertise from UCG, geological CO_2 storage, and enhanced oil recovery is being compiled, critically assessed, and used as building blocks in designing the hydrogen-oriented UCG plant. The concept of a georeactor that integrates UCG with geothermal heat exchange and with carbon capture and storage is being investigated.

2.4. China. It is generally believed that China has the largest UCG program currently underway. This is confirmed by the relatively large number of patents in the UCG area that have been obtained by Chinese engineers (see Figure 2). Since the late 1980s, many UCG trials have been carried out or are currently operating. Chinese trials utilize abandoned galleries of used 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 in the early 1930s in the USSR[45] for the production of hydrogen, in which a system of alternating air and steam injection is used. The experiments, conducted in Woniushan coal mine, Xuzhou, Jiangsu Province, confirmed the feasibility of using UCG for large-scale hydrogen production.[46]

Current technological projects include construction of a pilot industrial UCG plant at the Gonggou coal mine, Wulanchabu,

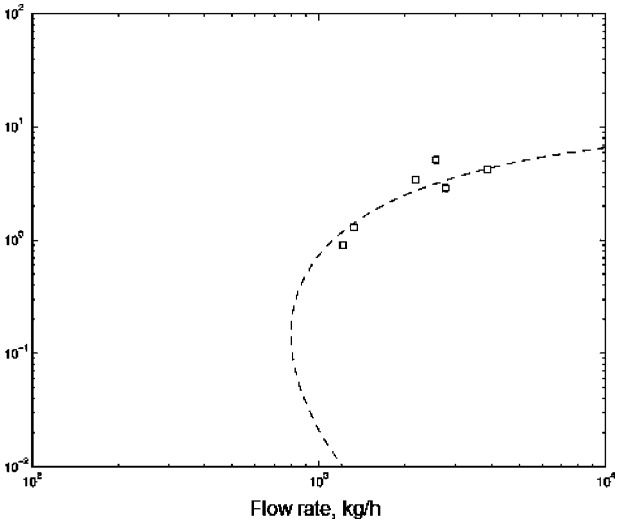

Figure 9. Predicted (curve) and experimental (points) speed of reverse combustion linking as a function of the air flow rate.[50]

Northern Inner Mongolia Autonomous Region. The $112 million project is a joint venture between the China University of Mining and Technology and Hebei Xin'ao Group.

2.5. Canada. In Canada, Ergo Exergy Technologies Inc. is a small but active UCG development company. According to the information on the company's Web site,[47] prior to founding the company in 1994, the principals of Ergo Exergy worked at the Angren UCG plant in Uzbekistan. Recently, Ergo Exergy experts completed a UCG trial in Australia (see section 2.6). They are currently working on a UCG pilot plant in South Africa (see section 2.7). It should be noted that, according to Ergo Exergy, they use their proprietary εUCG technology. Burton et al.[1] suggest the εUCG might be based on the old Soviet UCG technology.

Laurus Energy Inc., an exclusive Canadian licensee of the εUCG technology, is developing a commercial project targeting power generation and supply of fuel and hydrogen for the local industrial markets near Edmonton, Alberta, Canada. The started project development includes regulatory and environmental approvals, site selection and a prefeasibility study, and a site characterization program.[48] Note that coal gasification can be used to generate steam for oil recovery from tar sands, which are a major source of oil in Canada.[49]

In addition, Michael Blinderman, a director of Ergo Exergy, collaborates with researchers at the University of Queensland (Australia) in modeling the UCG process. Recently, they have developed new models for reverse and forward combustion regimes in UCG.[50−52] In contrast with the earlier model,[23,24] both oxygen-deficient and coal-deficient cases were analyzed. Hydrodynamic and pulsating stability were considered, and special attention was paid to the vicinity of the stoichiometric point. Also, curved flames were analyzed in this work. Along with asymptotic methodologies, in several instances, simplified formulations were used, and compact analytical representations were obtained. This approach resulted in an overall theory of reverse combustion linking during UCG that determines the relationships between key parameters of the process. Preliminary results of applying the theory to specific UCG conditions demonstrated reasonable conformity with the data obtained in practical UCG operations. For example, Figure 9 shows the speed of reverse combustion linking as a function of the supplied air flow rate. It can be seen that the predicted values are in good agreement with the experimental data from the Chinchilla trial. For forward combustion, a two-dimensional model was developed, assuming quasi-stationary flow of gas through a thin coal seam. It was shown that the speed and efficiency of forward combustion linking are significantly lower than those of reverse combustion, which correlates with prior experimental results.

2.6. Australia. The development of UCG technology in Australia was advocated by Prof. Ian Stewart of the University of Newcastle. In 1983, his program of laboratory research was followed by a government funded feasibility study of UCG at the Leigh Creek coal mine in South Australia. The study concluded that the use of UCG gas as a fuel for combustion in gas turbines would be cost competitive with other sources of power.[53] Currently, commercial UCG projects are being developed by at least three Australian companies: Cougar Energy Ltd., Linc Energy Ltd., and Carbon Energy Ltd.

The Managing Director of Cougar Energy, Dr. Len Walker, has actively pursued an interest in UCG since 1982. In 1996, he formed an association with Dr. Michael Blinderman from Ergo Exergy. Together, they initiated a UCG trial at Chinchilla in South East Queensland, conducted between 1999 and 2002.[54] Cougar Energy is planning to use Ergo Exergy's εUCG technology in the current projects. In Queensland, Cougar Energy has completed resource definition at its Kingaroy site and is undertaking final site characterization prior to commencing the pilot burn for a 400 MW combined-cycle power project. In Victoria, Cougar Energy's plan is to determine whether significant localized deposits of Victorian lignite exist that might be suitable for application of the UCG process.

The aforementioned Chinchilla trial was conducted by Linc Energy, using the technology provided by Ergo Exergy. The project involved drilling 9 injection/production wells and 19 monitoring wells to a coal seam at the average depth 140 m. During the project period, 35000 t of coal was gasified, with 95% recovery of the coal resource and 75% total energy recovery. This resulted in the production of 80×10^6 Nm^3 of gas (heating value, 4.5−5.7 MJ/m^3). Results from an evaluation of the product gas composition showed that gas turbine units can operate satisfactorily on air-blown UCG gas. A maximum capacity of 80000 N m^3/h (675 t of coal per day) was reached, and the availability of gas production over 30 months was demonstrated. The Chinchilla project also demonstrated the feasibility of controlling the UCG process, including shutdown and restart, and resulted in successful environmental performance according to independent audit reports. Specifically, no groundwater contamination was registered, no subsidence occurred, no surface contamination was detected, and no environmental issues were identified.

It should be noted that, at the end of 2006, the collaboration between Linc Energy and Ergo Exergy was terminated. In December 2006, Linc Energy signed cooperation agreements with the Skochinsky Institute of Mining in Moscow, Russia, and its parent organization, the Scientific-Technical Mining Association. In October 2007, Linc Energy acquired a controlling interest in Yerostigaz, which owns the UCG site in Angren in Uzbekistan. With the additional experienced employees and expertise from Russia and Uzbekistan, Linc Energy plans to move forward on expanding UCG operations in Australia (a commercial UCG and coal-to-liquids plant) and other countries.[53]

Carbon Energy Ltd. is using CRIP technology and modeling packages for site selection, process design, and process control, developed at the Commonwealth Scientific and Industrial Research Organization (CSIRO).[55] Carbon Energy plans a large-scale demonstration trial at Bloodwood Creek, in the Surat Basin in Queensland. In September 2008, Carbon Energy announced

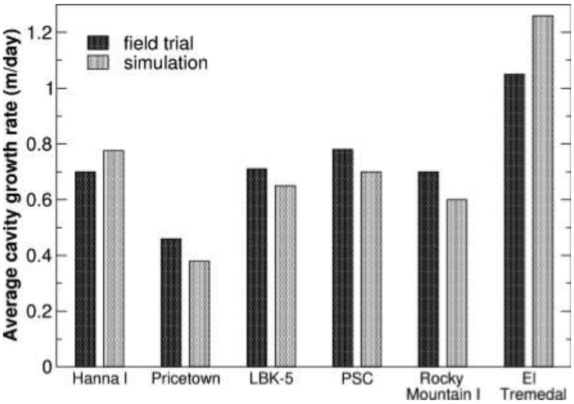

Figure 10. Comparison of estimated cavity growth rates from six UCG field trials with model simulations.[57]

successful completion of the directional drilling program, which involved creating two parallel 850-m-long in-seam wells and a vertical ignition well.[55] The trial will be performed as the first module of a commercial facility for generation of 1 PJ per year of syngas with a three-year module life. It is planned that each module will produce enough syngas to generate 20 MW of electricity in a combined-cycle gas-turbine power plant.

Along with the commercial developments described above, several research projects on the modeling of UCG processes have been conducted at CSIRO, the University of Queensland[50−52] (see section 2.5), and the University of New South Wales.[56−58] Perkins and Sahajwalla[56,57] developed a one-dimensional model of a reacting coal block to investigate the effects of operating conditions and coal properties on the local rate of cavity growth and energy effectiveness in UCG process. The investigation revealed that the cavity growth rate is most sensitive to the operating temperature, water influx, and gas pressure. The coal properties that most affect the cavity growth rate are the thermomechanical spalling behavior, the behavior of the ash, and the amount of fixed carbon in the coal. Many trends observed in the field trials are reproduced by the model simulations, and predicted cavity growth rates for six field trials are comparable to those observed (Figure 10).

More recently, Perkins and Sahajwalla[58] developed a two-dimensional axisymmetric CFD model of a UCG cavity partially filled with ash. Simulations revealed that, when bottom injection of the oxidant is applied, the flow in the void space above the ash bed is dominated by a single buoyant force due to temperature gradients established by combustion. Optimum oxygen injection rates can be found that maximize the production of chemical energy in the product gas. When the oxidant is injected into the cavity from the top, most of the valuable gasification products are oxidized, leading to a product gas with a high temperature and a low caloric value. The simulations elucidate the important transport and reaction processes occurring in the underground cavity, and the results are in qualitative agreement with observations from UCG field trials.

2.7. South Africa. Eskom, a coal-fired utility in South Africa, has been investigating UCG at its 4100 MW Majuba power plant since 2001, using Ergo Exergy's εUCG technology. By the end of 2008, the project generated about 15000 m^3/h of flared gas.[16] 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 the cofiring of 1200 MW of electricity at Majuba. 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 Gt 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 9-fold.[59]

2.8. New Zealand. In 1994, a UCG project was undertaken in the Huntly coal reserve, 120 km south of Auckland. The test was carried out over a 13-day period, and approximately 80 t of coal was consumed during reverse combustion linking of five vertical wells, which, however, was not followed by proper gasification.[16]

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 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 Ergo Exergy's εUCG technology within New Zealand and is currently investigating the potential for the application of UCG there.[60]

2.9. India. UCG is a promising technology for India, which has vast coal resources, primarily of low grade. India looks to utilize its coal reserves, which are the fourth-largest in the world, to reduce dependency on oil and gas imports. UCG is expected to be used to tap India's coal reserves, which are difficult to extract economically using conventional technologies. The Oil and Natural Gas Corporation Ltd. (ONGC) is planning to carry out pilot projects using recommendations of experts from the Skochinsky Institute of Mining in Moscow.[61] The Gas Authority of India Ltd. (GAIL) and AE Coal Technologies India Pvt. Limited, a company belonging to the Abhijeet Group of India, are implementing UCG projects using Ergo Exergy's εUCG technology.[62]

Recently, computational fluid dynamics studies of complex flow patterns in a growing UCG cavity were conducted by researchers of IIT-Bombay in collaboration with ONGC.[63] The main objective of this work was to understand the velocity distribution and perform residence time distribution (RTD) studies in the UCG cavity. Based on the RTD studies, the actual UCG cavity at different times was modeled as a simplified network of ideal reactors, which might offer a computationally less expensive and easier option to determine UCG process performance as a function of time.

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 and are considering conducting a trial in the near future. A feasibility study has been undertaken for a UCG trial, for which a 55 km^2 site area was selected.[64] Predictions were based on analysis of field data from UCG trials in the U.S. The study identified the largest cost elements as drilling and oxygen.

3. Criteria for UCG Site Selection

The determination of selection criteria for UCG locations is an important problem. The criteria for underground mining, including technological and land-use restrictions, are well-known, but in some cases, 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 applicable to mining.

3.1. Thickness of Coal Seam. The available information on the minimum seam thickness for UCG is somewhat contradictory. GasTech[5] indicates that the optimal thickness should be more than 10 m. However, that report considered coal seams of the Powder River Basin, Wyoming, which are mainly from 10 to over 30 m in thickness. On the contrary, Ergo Exergy states that UCG can be used in coal seams as thin as 0.5 m.[47] As mentioned above, UCG work in the FSU showed that the heating value of the produced gas decreases significantly with decreasing coal thickness below 2 m (see Figure 1), so this value might be considered a desirable lower limit.

3.2. Depth of Coal Seam. Our analysis of the 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 U.S. experiments, whereas Western European trials were conducted in much deeper coals (600−1200 m). The LLNL experts indicate that the minimum depth should be 12 m.[1] On the other hand, relatively shallow coal seams are generally used for surface mining. Sixty meters is the typically applied limit to the depth of surface mining and is therefore considered a bounding limit in this analysis. For example, the Indiana Geological Survey has used 200 feet (∼60 m) as the maximum depth for surface mining.[65] Taking into account the relatively low cost of surface mining and assuming that use of this technology will continue, it is reasonable to expect that coals with depths of less than 60 m have low suitability for UCG. Additionally, the proximity of potable and potentially potable groundwater supplies at this shallow depth discourages further consideration of those coals that are located near the ground surface.

To decrease the risk of subsidence, Burton et al.[1] recommend operational depths of >200 m. Depths of more than 300 m require more complicated and expensive drilling technologies, but they also have advantages such as minimized risk of subsidence and the possibility of conducting the UCG process at higher pressure, which increases the heating value of the produced gas. Also, deeper seams are less likely to be hydrologically linked with potable aquifers, thus avoiding drinkable water contamination problems. Further, if the product gas is to be used in gas turbines, additional compression might not be necessary. Finally, UCG cavities at depths of more than 800 m could be used for CO_2 sequestration.

If potential UCG sites are found at different depths, further analysis should be made based on tradeoffs between the higher costs of deeper wells and the advantages of UCG production from greater depths. As mentioned above (see section 2.3), a major advantage of using deeper coals for UCG is the higher gasification pressure, which yields a higher methane content and hence a higher heating value. Of course, if the intent is to produce chemicals and/or liquid fuels from the gasified coal, then maintaining high CO and H_2 contents, rather than a high percentage of methane, is of interest.

3.3. Coal Rank and Other Properties. With the present state of knowledge, low-rank, high-volatility, noncaking bituminous coals are preferable. UCG might work better on lower-rank coals because such coals tend to shrink upon heating, enhancing permeability and connectivity between injection and production wells.[1] Also, the impurities in lower-rank coals might improve the kinetics of gasification by acting as catalysts for the burn process. For coals of the same rank, the heating value of the UCG gas increases with increasing heating value of the coal.

The values of porosity and permeability within the coal seam might also be important factors, but it is difficult to use them as criteria at this point because of the scarcity of such data. Better cleated and more permeable seams allow for more effective connection between the injection and production wells, leading to faster transport of reactants and a higher rate of gasification. 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.[6] have stated that, in general, reverse combustion works well in shallow nonswelling coal but is not recommended for use at great depths and in swelling coals. This contradicts, however, the opinion of Burton et al.,[1] who noted that the FSU methods demonstrated minimum sensitivity to coal swelling: the large-dimension channels formed in the linkage process employed in those operations did not appear 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 that could potentially provide a pathway for water inflow or gas migration should be preferentially targeted.[7]

3.4. Dip of Coal Seam. Sury et al.[7] have indicated that shallow dipping coal seams are preferable. Such seams facilitate drainage and the maintenance of hydrostatic balance within the gasifier; they also minimize potential damage to the down dip production well from material that is moved in association with the UCG process. A report by GasTech[5] recommends dip angles of 0−20°. However, UCG has been successfully carried out in steeply dipping seams;[8] thus, dip is not a critical constraining factor for selecting and operating UCG sites.

3.5. Groundwater. Water is an essential component of the UCG process, and thus its availability either from within a coal seam or from a source adjoining the seam is an important characteristic. The adjoining rocks must contain saline water (>10000 ppm total dissolved solids, as per U.S. Environmental Protection Agency regulations) and have a significant deliverable volume. In many cases, the coal itself serves as the principle aquifer within the stratigraphic section and is bounded by impermeable shales and low-density rock. In some cases, permeable sandstones form the roof rock and therefore are in hydrological connectivity with strata outside the coal seam. Sury et al.[7] recommended using coal seams with no overlying potable aquifers within a distance of 25 times the seam height. Trials have been successfully carried out in seams in closer proximity to potable underground aquifers, but the potential risk of contamination increases in such a setting.

3.6. Amount of Coal. Gas produced by the underground gasification process can potentially be used in several applications. These applications range from supplying mobile units that could provide gas in agricultural areas to supporting large power and chemical plants producing hundreds to thousands of megawatts 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 in a gasification project in conjunction with a consideration of the potential applications of the produced gas. Additionally, for each potential site, the productive lifetime of the site must be determined as a function of required gas yield. For illustration, for 20-year continuous operation of a 300 MW UCG-based combined-cycle power plant (efficiency, 50%), it is necessary to produce 75.6×10^9 Nm^3 of syngas with a heating value of 5 MJ/m^3. Based on the Chinchilla experimental data (see section 2.6), 33×10^6 metric tons needs to be gasified for this purpose. Note that this amount can be decreased by a factor of 2 by using oxygen and steam as injection gases, which, however, increases the cost.

3.7. Land-Use Restrictions. There is no indication in the literature that UCG should be farther from towns, roads, and other objects than underground mines, assuming that the process design and environmental monitoring eliminate water contamination and air pollution. Thus, the land-use restrictions for underground mining can be applied to potential UCG sites.

4. Summary and Recommendations

Our analysis of the current status of UCG shows that this technology has a great potential to grow and replace/complement traditional methods for coal mining and surface gasification. New commercial UCG projects have started recently in several countries, and more projects will probably start soon. Selection of the best UCG technology is a complex process, and a variety of technical and geological factors must be taken into consideration for each site being evaluated.

Acknowledgment

It is a pleasure to participate in this celebration of Professor J. B. Joshi. Acknowledgment is made to the Indiana Center for Coal Technology Research for financial support of this work. The authors also thank Drs. Maria Mastalerz and John Rupp of the Indiana Geological Survey for useful discussions, as well as reviewers for thorough reviews of the manuscript and helpful suggestions.

Literature Cited

(1) Burton, E.; Friedmann, J.; Upadhye, R. *Best Practices in Underground Coal Gasification*; Contract W-7405-Eng-48; Lawrence Livermore National Laboratory: Livermore, CA, 2006.

(2) Creedy, D. P.; Garner, K. *Clean Energy from Underground Coal Gasification in China*; DTI Cleaner Coal Technology Transfer Programme; Report COAL R250; DTI/Pub URN 03/1611; Department of Trade and Industry Technology (DTI): London, 2004.

(3) Creedy, D. P.; Garner, K.; Holloway, S.; Jones, N.; Ren, T. X. *Review of Underground Coal Gasification Technological Advancements*; Report COAL R211; DTI/Pub URN 01/1041; Department of Trade and Industry Technology (DTI): London, 2001.

(4) *Review of the Feasibility of Underground Coal Gasification in the UK*; Cleaner Fossil Fuels Programme; DTI/Pub URN 04/1643; Department of Trade and Industry Technology (DTI): London, 2004.

(5) *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; GasTech, Inc.: Casper, WY, 2007.

(6) Sury, M.; White, M.; Kirton, J.; Carr, P.; Woodbridge, R.; Mostade, M.; Chappell, R.; Hartwell, D.; Hunt, D.; Rendell N. *Review of Environmental Issues of Underground Coal Gasification*; Report COAL R272; DTI/Pub URN 04/1880; Department of Trade and Industry Technology (DTI): London, 2004.

(7) Sury, M.; White, M.; Kirton, J.; Carr, P.; Woodbridge, R.; Mostade, M.; Chappell, R.; Hartwell, D.; Hunt, D.; Rendell N. *Review of Environmental Issues of Underground Coal Gasification—Best Practice Guide*; Report COAL R273; DTI/Pub URN 04/1881; Department of Trade and Industry Technology (DTI): London, 2004.

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

(9) Lazarenko, S. N.; Kreinin, E. V. *Underground Coal Gasification in Kuzbass: Present and Future*; Institute of Coal, Siberian Branch of the Russian Academy of Sciences, Nauka: Novosibirsk, Russia, 1994 (in Russian).

(10) Lazarenko, S. N.; Kreinin, E. V. *Underground Coal Gasification in Kuzbass: New Opportunities*; Institute of Coal and Geochemistry, Siberian Branch of the Russian Academy of Sciences: Kemerovo, Russia, 2006 (in Russian).

(11) Gregg, D. W.; Edgar, T. F. Underground Coal Gasification. *AIChE J.* **1978**, *24*, 753–781.

(12) Kreinin, E. V.; Fedorov, N. A.; Zvyagintsev, K. N.; Pyankova, T. M. *Underground Gasification of Coal Seams*; Nedra: Moscow, Russia, 1982 (in Russian).

(13) Antonova, R. I.; Bezhanishvili, A. E.; Blinderman, M. S. *Underground Coal Gasification in the USSR*; TsNIEIugol: Moscow, Russia, 1990 (in Russian).

(14) Kreinin, E. V.; Dvornikova, E. V. Does In-Situ Gasification of Coal Seams Cause Pollution of Underground Water. *Ugol′* **1993**, *4*, 39–40 (in Russian).

(15) Dvornikova, E. V. Role of Sorption Properties of GZh-Grade Coal in Self-Purification of Groundwaters. *Ugol′* **1996**, *5*, 45–47 (in Russian).

(16) Blinderman, M. S. Ergo Exergy, Montreal, Canada. Personal communication, 2008.

(17) Kreinin, E. V.; Shifrin, E. I. Mathematical Model of Coal Combustion and Gasification in a Passage of an Underground Gas Generator. *Combust., Explos., Shock Waves* **1993**, *29*, 148–154.

(18) Den'gina, N. I.; Kazak, V. N.; Pristash, V. V. Changes in Rocks at High Temperatures. *J. Min. Sci.* **1994**, *29*, 472–477.

(19) Kreinin, E. V.; Dvornikova, E. V. Forecast of Spreading of Zones of Pollution Source Interaction with Groundwater. *Dokl. Akad. Nauk* **1999**, *365* (3), 371–373 (in Russian).

(20) Database of the European Patent Office available at http://ep.espacenet.com/?locale=en_ep (accessed March 2009).

(21) Database of the World Intellectual Property Organization (WIPO) available at http://www.wipo.int/pctdb/en (accessed March 2009).

(22) Hill, R. W. Review of the CRIP Process. In *Proceedings of the 12th Annual Underground Coal Gasification Symposium*; DOE: Washington, DC, 1986 (Report DOE/FE/60922-H1).

(23) Britten, J. A.; Krantz, W. B. Linear Stability of Planar Reverse Combustion in Porous Media. *Combust. Flame* **1985**, *60*, 125–140.

(24) Britten, J. A.; Krantz, W. B. Asymptotic Structure of Planar Nonadiabatic Reverse Combustion Fronts in Porous Media. *Combust. Flame* **1986**, *65*, 151–161.

(25) Britten, J. A.; Thorsness, C. B. A Model for Cavity Growth and Resource Recovery during Underground Coal Gasification. *In Situ* **1989**, *13*, 1–53.

(26) Morris, J.; Vorobiev, O.; Antoun, T.; Friedmann, S. J. Geomechanical Simulations Related to UCG Activities. Presented at the *Twenty-Fifth Annual International Pittsburgh Coal Conference*, Pittsburgh, PA, Sep 29−Oct 2, 2008; Paper 32-3.

(27) *BP and LLNL Sign Technical Cooperation Agreement on Underground Coal Gasification*; LLNL News Release NR-07-07-03; Lawrence Livermore National Laboratory: Livermore, CA, 2007; available athttps://publicaffairs.llnl.gov/news/news_releases/2007/NR-07-07-03.html.

(28) Friedmann, S. J. North America Prospects for UCG in a Carbon Constrained, Energy Secure World. Presented at the *Twenty-Fifth Annual International Pittsburgh Coal Conference*, Pittsburgh, PA, Sep 29−Oct 2, 2008; Paper 26-1.

(29) Blinderman, M. S.; Friedmann, S. J. *Underground Coal Gasification and Carbon Capture and Storage: Technologies and Synergies for Low-Cost, Low-Carbon Syngas and Secure Storage*; Report UCRL-ABS-218560; Lawrence Livermore National Laboratory: Livermore, CA, 2006.

(30) Gadelle, C.; Lessi, J.; Sarda, J. P. Underground Coal Gasification at Great Depth. The French Field Test of Bruay-En-Artois. *Oil Gas Sci. Technol. Rev. IFP* **1982**, *37*, 157–181.

(31) Gadelle, A.; Pavone, D.; Raffoux, J.; Ternot, A. Status of French UCG Field Test at La Haute Deule. In *Proceedings of the 11th Annual Underground Coal Gasification Symposium*; DOE: Washington, DC, 1985; pp 92−106 (Reports DOE/METC-85/6028, DE85013720).

(32) Chandelle, V.; Fabry, R.; Kurth, M.; Li, T. K.; Patigny, J.; Sonntag, C. Overview about Thulin Field Test. In *Proceedings of the 12th Annual Underground Coal Gasification Symposium*; DOE: Washington, DC, 1986; pp 53−59 (Report DOE/FE/60922-H1).

(33) Kurth, M.; Depouhon, F.; Patigny, J.; Ledent, P. Linking and Gasification in Thulin, A New Endeavor. In *Proceedings of the 12th Annual Underground Coal Gasification Symposium*; DOE: Washington, DC, 1986; pp 60−65 (Report DOE/FE/60922-H1).

(34) Chandelle, V. The Pushing Through Project of the Gasification Channel in Tulin Coal Field. *Collect. Translat. Works Min. Technol.* **1992**, *13* (2), 5–7.

(35) Green, M. B. *Underground Coal Gasification—A Joint European Trial in Spain*; Report Coal R196; DTI Pub URN99/1093; Department of Trade and Industry Technology (DTI): London, 1999.

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

(37) Van Batenburg, D. W.; Biezen, E. N. J.; Bruining, J. A New Channel Model for Underground Gasification of Thin, Deep Coal Seams. *In Situ* **1994**, *18*, 419–451.

(38) Kuyper, R. A.; van der Meer, T. H.; Hoogendoorn, C. J. Turbulent Natural Convection Flow due to Combined Buoyancy Forces during Underground Coal Gasification of Thin Seams. *Chem. Eng. Sci.* **1994**, *49*, 851–861.

(39) Kuyper, R. A.; van der Meer, T. H.; Bruining, J. Simulation of Underground Gasification of Thin Coal Seams. *In Situ* **1996**, *20*, 311–346.

(40) Coeme, A.; Pirard, J. P.; Mostade, M. Modeling of the Chemical Processes in a Longwall Face Underground Gasifier at Great Depth. *In Situ* **1993**, *17*, 83–104.

(41) Mathy, B.; Pirlot, P.; Pirard, J. P.; Coeme, A.; Mostade, M.; De Ro, P. Flow Modeling in an Underground Gasifier at Great Depth by the Boundary Element Method. *In Situ* **1994**, *18*, 399–418.

(42) Pirlot, P.; Pirard, J. P.; Coeme, A.; Mostade, M. A Coupling of Chemical Processes and Flow in View of the Cavity Growth Simulation of an Underground Coal Gasifier at Great Depth. *In Situ* **1998**, *22*, 141–156.

(43) Wilks, I. H. C. The Cavity Produced by Gasifying Thin Deep Seams. In *Proceedings of the 9th Annual Underground Coal Gasification Symposium*; DOE: Washington, DC, 1983; pp 314−322 (Report DOE/MET C/84-7).

(44) Rogut, J.; Steen, M. Hydrogen Oriented Underground Coal Gasification of Coal. Presented at the *Twenty-Fifth Annual International Pittsburgh Coal Conference*, Pittsburgh, PA, Sep 29−Oct 2, 2008; Paper 20-3.

(45) Kreinin, E. V. Two-stage In-situ Coal Gasification. *Khim. Tverd. Topl.* **1990**, *6*, 76–79 (in Russian).

(46) Yang, L.; Zhang, X.; Liu, S.; Yu, L.; Zhang, W. Field Test of Large-Scale Hydrogen Manufacturing from Underground Coal Gasification (UCG). *Int. J. Hydrogen Energy* **2008**, *33*, 1275–1285.

(47) See http://www.ergoexergy.com (accessed March 2009).

(48) Maev, S. Development of a UCG Based Project in Canada. Presented at the *Twenty-Fifth Annual International Pittsburgh Coal Conference*, Pittsburgh, PA, Sep 29−Oct 2, 2008; Paper 32-6.

(49) Du Plessis, D. Gasification: A Key Technology Platform for Western Canada's Coal and Oil Sands Industries. Presented at the *Twenty-Fifth Annual International Pittsburgh Coal Conference*, Pittsburgh, PA, Sep 29−Oct 2, 2008; Plenary Lecture.

(50) Blinderman, M. S.; Klimenko, A. Y. Theory of Reverse Combustion Linking. *Combust. Flame* **2007**, *150*, 232–245.

(51) Blinderman, M. S.; Saulov, D. N.; Klimenko, A. Y. Exergy Optimisation of Reverse Combustion Linking in Underground Coal Gasification. *J. Energy Inst.* **2008**, *81*, 7–13.

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

(53) See http://www.lincenergy.com.au (accessed March 2009).

(54) See http://www.cougarenergy.com.au (accessed March 2009).

(55) See http://www.carbonenergy.com.au (accessed March 2009).

(56) Perkins, G.; Sahajwalla, V. A Mathematical Model for the Chemical Reaction of a Semi-infinite Block of Coal in Underground Coal Gasification. *Energy Fuels* **2005**, *19*, 1679–1692.

(57) Perkins, G.; Sahajwalla, V. A Numerical Study of the Effects of Operating Conditions and Coal Properties on Cavity Growth in Underground Coal Gasification. *Energy Fuels* **2006**, *20*, 596–608.

(58) Perkins, G.; Sahajwalla, V. Modelling of Heat and Mass Transport Phenomena and Chemical Reaction in Underground Coal Gasification. *Chem. Eng. Res. Des.* **2007**, *85* (A3), 329–343.

(59) See http://www.eskom.co.za (accessed March 2009).

(60) Pearce, S. Maximizing the Potential of UCG by Leveraging Core Mining Competencies. Presented at the SYNGAS Refiner's 2008 Underground Coal Gasification Conference, Houston, TX, Jul 16−17, 2008; see http://www.syngasrefiner.com/ucg/agenda.asp (accessed March 2009).

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

(62) Jayaswal A. Underground Coal Gasification in India−An Initiative by AE Coal Technologies. Presented at the *SYNGAS Refiner's 2008 Underground Coal Gasification Conference*, Houston, TX, Jul 16−17, 2008; see http://www.syngasrefiner.com/ucg/agenda.asp (accessed March 2009).

(63) Aghalayam P.; Sateesh D.; Naidu, R.; Mahajani, S.; Ganesh, A.; Sapru R. K.; Sharma R. K. Compartment Modeling for Underground Coal Gasification Cavity. Presented at the *Twenty-Fifth Annual International Pittsburgh Coal Conference*, Pittsburgh, PA, Sep 29−Oct 2, 2008; Paper 32-4.

(64) Shimada, S.; Tarmari, A.; Ishii, E. Feasibility Study on Underground Coal Gasification in Japan. *Shigen-to-Sozai (J. Min. Mater. Process. Inst. Jpn.)* **1994**, *110*, 64–68.

(65) Mastalerz, M.; Drobniak, A.; Rupp, J.; Shaffer, N. *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; Indiana University: Bloomington, IN, 2004.

Received for review October 17, 2008
Revised manuscript received April 14, 2009
Accepted April 15, 2009

IE801569R