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Commercial development of underground coal gasification

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Underground coal gasification (UCG) is a process by which coal seams at depths uneconomic for open pit mining can be converted, using drillhole access, to a gas suitable for use as a fuel for power generation or as a chemical feedstock. Its application draws on a wide range of engineering and related disciplines including chemistry, geology, geohydrology, geotechnical engineering (including drilling techniques) and chemical engineering. This paper describes the UCG process and traces its historical development with particular reference to the vast amount of work undertaken in the former Soviet Union since the 1930s. Reference is also made to the most recent UCG tests in Australia (1999–2002), Spain (1997) and the USA (1987–1988), and to the new generation of projects that are in various stages of planning and development. The significance of the required specialist technical disciplines is discussed, and both environmental and commercial issues of specific relevance to UCG project development are reviewed.

1. INTRODUCTION

As part of the current debate on climate change, governments in a number of countries are calling for energy sources that combine low prices with increased efficiency in resource utilisation, reduced greenhouse gas emissions and improved environmental outcomes. While a strong case is being mounted for the development of renewable forms of energy such as wind power, solar power and the production of biofuels, it is recognised that the low cost and plentiful supplies of coal internationally make its replacement as a significant energy source unlikely for many years. As a result, focus has been placed on the development of so-called clean coal technologies that might meet the above energy source objectives. Underground coal gasification (UCG) is one such technology, which is only now achieving commercial acceptance in the West, despite its long history of development in the former Soviet Union (FSU).

2. THE UCG PROCESS

The UCG process is initiated by drilling two adjacent boreholes into a coal seam, with both vertical and/or deviated drillholes being utilised. A pressurised oxidant such as air or oxygen/steam is then injected into one of the boreholes and ignited at the coal seam. The resulting chemical reactions within the seam convert the coal to a gas, which is then extracted through the second borehole. Ash and inert material from interbedding remain in the cavity. The product gas is collected at the surface and treated to remove residues and contaminants, after which it can be used as either a fuel gas for power generation or a synthesis gas for petrochemical processes. Expansion of the process is achieved by the addition and linkage of further injection and production wells.

As the underground reaction proceeds, a void is created that extends to the roof of the coal seam; this void eventually collapses into the burnt-out cavity as the reaction zone moves away. A schematic diagram illustrating the process is shown in Fig. 1. The pressurised gases in the cavity are prevented from escaping by overlying impermeable rocks and by pore water pressure in the surrounding coal and overburden, maintained by the permanent water table. As a result of these factors, operations are best conducted at depths exceeding 100 m, that is generally beyond the limits of conventional open cut mining.

The chemical reactions involved in the UCG process have been described by Davis and Jennings.[1] The 'coal gas' produced has a low calorific value, and is a mixture of hydrogen, carbon monoxide, methane, carbon dioxide and higher hydrocarbons, with nitrogen if air is used in the process. The calorific value is approximately one-eighth of natural gas if air injection is used, and double this figure if oxygen injection is used. After preparation, the gas can be used to fuel a gas turbine or other chemical processing plant. With appropriate UCG technology, the cost of the gas per unit of energy is typically less than half that of natural gas. When compared with current coal-fired power generation, these factors combine to provide a competitive cost of power at a smaller scale, with lower carbon dioxide (CO_2) emissions and longer term potential for CO_2 sequestration.

3. UCG DEVELOPMENT HISTORY

The historical development of UCG has been summarised by Lamb[2] and Walker,[3] and can perhaps most conveniently be considered in two distinct parts—activities in the FSU and activities in the western world.

3.1. FSU activity

UCG was first advanced in Europe by Siemens in 1868 and in the former USSR by Mendeleyev in 1888. Scientific research into UCG was initiated in Britain in 1913 and the concept was

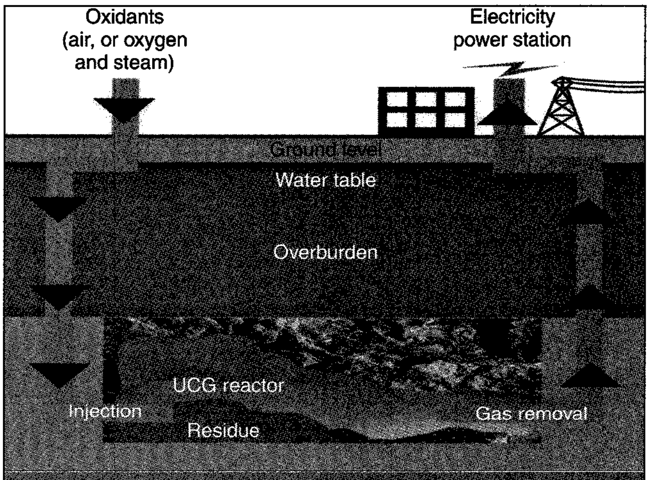

Fig. 1. UCG production process

taken up by Lenin in the FSU, leading to the initiation of research work there in the 1930s.

Research, development and operational activity in the FSU continued strongly through to the 1960s, but declined towards the end of that decade. Gregg *et al.*,[4] in a review for the US Government of Soviet work in UCG, attributed this decline to the discovery of large resources of natural gas and the effort required for associated pipeline construction. They also estimated that the replacement cost of all the research, development and operational work undertaken in the FSU to that time might be as much as US$10 billion 1976 dollars.

While the magnitude of this expenditure is massive, of perhaps equal importance in today's context is the expertise gained in handling variable geological conditions. On this matter, Gregg *et al.*[4] concluded that experience in the FSU provided the design capability to operate in a predictable manner and to transfer this capability between sites with quite different geological features.

Both Gregg *et al.*[4] and Dossey[5] describe operations at a number of Soviet UCG sites. Dossey estimated that by 1963, a total of 1·4 billion m^3/year of gas of low calorific value was being produced in the USSR, of which 63% was produced at the Angren plant, which is still operating. This figure is confirmed by Kreinin,[6] an active participant in the Russian programme, who estimated that about 15 Mt of coal had been gasified in the USSR, with more than 50 billion m^3 of gas produced.

3.2. Western world activity

Although UCG activities have been undertaken in a number of countries outside the FSU, the majority of activity in the West has been focused in the USA. Beaver *et al.*[7] summarised this activity, which became more intense after 1972. They tabulated some 28 different individual tests at 11 different locations over the period 1967–1988. It is estimated that over the entire period of the US test programme, approximately 50 000 t of coal was gasified—approximately 0·3% of Kreinin's 1992 figure for the FSU.

The longest and most well reported of these tests was undertaken in 1987–1988 near Hanna, Wyoming. Designated the Rocky Mountain 1 (RM1) test,[8] it incorporated a demonstration of the so-called Crip (controlled retracting injection point) process, which involves the use of a retracting horizontal hole in the coal seam for oxidant injection. The test used oxygen injection and produced a heating value gas of up to 9·0 MJ/m^3. Undertaken over a three-month period, the test consumed approximately 10 000 t of coal.

A number of small tests have been undertaken intermittently in Europe over the past 50 years, the most recent of which was in Spain in 1997. This test gasified approximately 300 t of coal at a depth of about 550 m over a period of 12 days. The test encountered difficulty due to the presence of an aquifer above the coal seam and an explosion associated with methane gas near the injection point.[9] The explosion was attributed to the ignition of methane gas that had built up after the pilot flame at the igniter self-extinguished. A number of recommendations for improvements to ignition systems were made as a result of this experience.

In Australia, the commercial potential for UCG received some attention during the 1980s, as a result of international interest in the process and the high oil prices of the 1970s. Funds were provided by a Federal Government grant for an evaluation of the significance of the UCG process for Australia. This work was directed by the late Professor Ian Stewart of the University of Newcastle, who drew heavily on the Russian experience in recommending that the technology be developed in Australia.

This evaluation led to a feasibility study in 1983 into the economics of developing a UCG facility at the Leigh Creek mine in South Australia, with combustion of the product gas in a gas turbine. The study concluded that electricity could be produced at a competitive price using the UCG process; however, no further funds were made available for development of the proposed facility.

3.3. Recent developments

Apart from completion of the Spanish test in 1997, there was little or no evident interest internationally in UCG in the 1990s, probably consistent with the then low oil price of less than US$ 25/bbl. However from 1997, the author led the development of a successful UCG pilot test at a site near Chinchilla, Queensland. The pilot test ran from 1999 to 2002 before it was shut down for lack of commercialisation finance. During this time it[10,11]

(*a*) gained initial environmental approval from the Queensland EPA
(*b*) gasified approximately 32 000 t of coal
(*c*) produced approximately 80 million m^3 of gas, with a calorific value of about 5 MJ/N m^3
(*d*) operated continuously for over 28 months, utilising nine process wells
(*e*) successfully met all environmental requirements during operation and decommissioning
(*f*) produced no impact on regional groundwater as verified by monitoring[12]
(*g*) provided data to verify the low cost of the produced gas and its suitability for cleanup and combustion in commercial gas turbines.

Figure 2 shows the continuous nature of gas production from the Chinchilla site, while Fig. 3 illustrates the minimal site disturbance resulting from installation of the UCG operation.

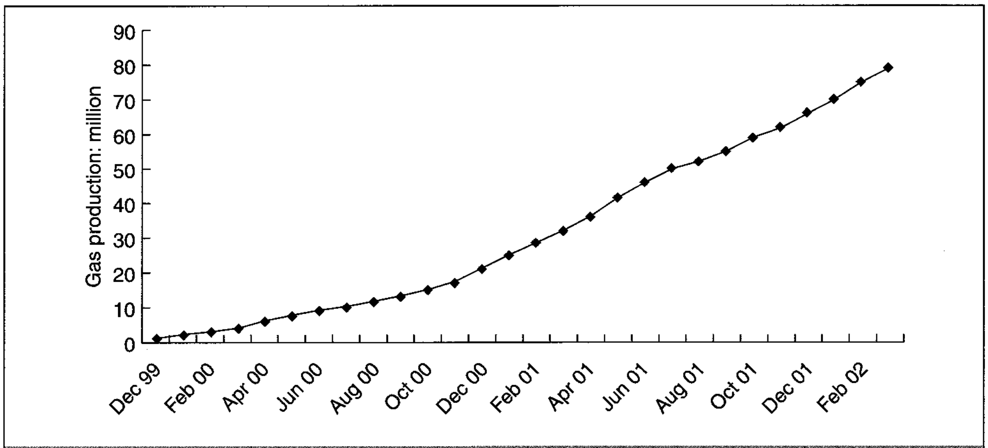

Fig. 2. Chinchilla UCG gas production, December 1999 to February 2002 (after Blinderman and Jones[11])

Since completion of the Chinchilla pilot burn, particularly in the past few years, there has been a quite remarkable acceleration in international UCG activity and the number of developmental projects being investigated. At a conference held in Houston in June 2007,[13] papers were presented on potential projects in the Majuba coalfield in South Africa (ignition successfully completed), Kingaroy in Australia (site characterisation planned), Powder River Basin in the USA (partners being sought) and Alberta, Canada (finance being finalised), as well as reference to specific projects in India and Pakistan.

The South African project is operated by Eskom, which supplies more than 90% of the country's power requirements (221 000 GWh in 2006). Ignition of the coal seam occurred on 20 January 2007, with UCG technology being supplied by Ergo Exergy Technologies Inc. of Canada. The project is planned to be developed in a series of stages to ultimately produce 2100 MW of power using UCG gas in a combined cycle power plant. The Kingaroy project, operated by Cougar Energy Ltd, is currently in the site characterisation stage and also involves Ergo Exergy Technologies as technology supplier. Ignition is planned for mid-2008 with an ultimate 400 MW proposed power generation.

In addition to the above projects, media releases over recent years confirm that the Chinchilla project has been restarted (ignition announced in September 2007), a new project nearby has been proposed (site characterisation commencing shortly), a preliminary study has been undertaken on the feasibility of gasifying coal seams deep below the Firth of Forth in Scotland and a greenfields UCG project is under development in China.

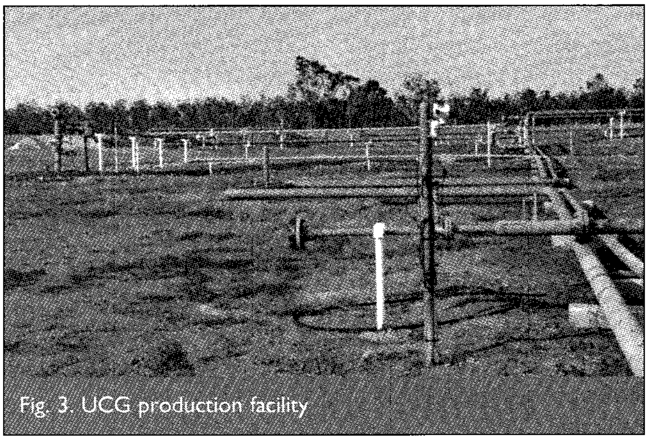

Fig. 3. UCG production facility

It is remarkable that this spread of projects has been generated in such a relatively short time frame. There are a number of reasons why this has occurred, including

(*a*) increasing confidence in the credibility of the technology resulting from successful UCG gas production in Australia and now South Africa
(*b*) rapid increases in energy costs triggered by the oil price jump from US$ 20/bbl in 2002 to US$ 100/bbl in 2007
(*c*) the emphasis on clean coal technologies as a means to achieve greenhouse gas emission reductions, specifically in power generation.

It appears that each of these factors will continue to be applicable over the next decade and, as a consequence, the momentum towards the development of commercial UCG projects will continue.

4. TECHNICAL ISSUES

4.1. Site characterisation

The simplistic description of the UCG process given in this paper belies the complexities of site selection, process initiation and expansion, and overall commercial project development. The selection of a coal deposit for development requires commercial considerations such as resource size and location, and the end use of the product gas–the kind of issues that are typical of any resource project development. There are, however, special features of the UCG process that require particular attention be given to a comprehensive site characterisation programme.

Geological, geotechnical and hydrogeological issues are paramount in the selection of a site suitable for application of UCG techniques. The geological evaluation of the site requires a comprehensive representation of the coal seam, as well as of the overlying and underlying strata. Geotechnical factors such as the strength, jointing and deformability of the overlying strata all have a role to play in the response of the profile to the process occurring in the coal seam.

As with conventional underground mining, the groundwater regime must be defined, both regionally and in the vicinity of the operation. Groundwater pressures in the coal seam and its permeability to water flow are integral to the UCG process operation. They govern the oxidant injection pressure that can be used and the potential water flow into the gasification cavity, which will impact on the chemistry of the reaction in the chamber. The presence of significant aquifer systems in the profile, particularly above the coal seam, may be impacted by subsidence resulting from roof collapse into the process cavity with potentially disastrous consequences to the operation.

While all of these issues are important, they can be addressed by engineering and geological procedures that are accepted in the specialist professions, although it is their collective impact on the UCG process that requires careful attention. The significance of a comprehensive and professional site characterisation programme is thus paramount to the success of any UCG project development.

4.2. Process technology

Such emphasis on site characterisation presumes the application of an appropriate process technology for the initiation and continuation of the UCG process. The current momentum in UCG project activity utilises technology that resulted from the operational expertise developed in the FSU and the experience gained with techniques developed in testing programmes in the United States in the 1980s.

While it is beyond the scope of this paper to discuss process technology in detail and the relevant expertise that resides largely as confidential know-how with its practitioners, it is evident that any planned UCG site evaluation or project development must be integrated with the requirements of the provider of the technology.

5. ENVIRONMENTAL IMPACTS

There are a number of environmental advantages of using UCG as a fuel source

- (*a*) elimination of major land disturbance (as required for open cut mining) and minimisation of rehabilitation work after completion of operations
- (*b*) removal of human safety concerns associated with underground mining
- (*c*) efficient use of coal resource compared with coal seam methane recovery
- (*d*) ash and other solid waste products produced in the process remain underground
- (*e*) reduced CO_2 emissions compared with coal-fired power generation when combined cycle power plant is used
- (*f*) ability economically to fuel power stations of small capacity, giving development flexibility with respect to both size and location.

There are also a number of environmental and social issues that must receive specific attention as part of planning for a commercial UCG project.

- (*a*) *Planning.* The selection of a UCG development site must meet all local planning and environmental regulations, such that potential social impacts are minimised. Ongoing communication with local communities is essential.
- (*b*) *Process control.* The UCG process is controlled by the location of injection and production wells; the absence of oxygen prevents the process from expanding outside the operating area.
- (*c*) *Safety.* Worker safety is aided by the remote operation and control of the underground process from the surface, as distinct from conventional underground mining operations.
- (*d*) *Gas leakage.* Experience from UCG working sites shows that gas leakage at the surface can be maintained below measurable limits. This follows from the selection of a coal deposit in surrounding rocks, the permeability and groundwater characteristics of which are acceptable.
- (*e*) *Subsidence.* Ground subsidence will occur after an area has been worked out, as occurs for underground mining, but with no sudden changes in surface level. When distributed over a large working area, the visual impact is minimal, although some changes in surface drainage patterns may occur and must be handled as part of site remediation.
- (*f*) *Groundwater.* Control of the UCG process involves injection pressures in the working cavity that are kept below adjacent groundwater pressures, so that water flow is into the cavity and liquid by-products of the underground process (water and liquid hydrocarbons) are removed by borehole to the surface in gaseous form.

Actual groundwater behaviour has been monitored in detail at the successful Chinchilla and RM1 sites. Oxidant injection pressures at these sites were maintained below the in situ groundwater pressure in the coal seam, thus ensuring that groundwater flow during operations was into the cavity. As a result, monitoring data[12] confirmed that no impacts were generated in the groundwater as a result of UCG operations.

Of particular relevance to the current debate about the impacts of global warming and the need significantly to reduce greenhouse gas emissions is the advantage of the UCG process in converting the energy contained in coal into a gaseous form that can be fed directly into a combined cycle power plant, with its high efficiency of conversion of input energy into electricity. In a case study of the life cycle emissions from a 400 MW power plant fuelled by UCG gas, BHP Billiton[14] concluded that around 25% less greenhouse gases would be emitted compared with the most efficient Australian coal-fired power stations. Such a benefit would be gained before any consideration is given to the additional benefits derived from the potential extraction and sequestration of CO_2 from the product gas.

Using Surat coal as a reference, the study calculated CO_2 emissions of 708 kg/MWh for the UCG plant, compared with 904 kg/MWh for a pulverised fuel (Pf) plant with conventional steam cycle and 817 kg/MWh for a Pf plant with a supercritical steam cycle. Some care is necessary in making these comparisons, as life cycle calculations for Pf plants require assumptions about CO_2 and methane emissions during coal mining and transportation that may be difficult to verify.

6. COMMERCIAL ISSUES FOR THE FUTURE

Up to the late 1990s, almost all of the activity in UCG process development had been the result of government sponsorship, either directly to research establishments or by funding to industry. This applies to the long-term funding in the FSU, the Department of Energy funding of the pilot trials in the USA during the 1970s and 80s, and funding of the working group in Europe, which led to the Spanish trial.

The reason for this government support appears to be a combination of factors, including a concern for worker safety (the driver behind the FSU work), high energy prices, an associated desire to make better utilisation of national coal resources and, more recently, a concern to develop clean coal technologies, specifically leading to lower greenhouse gas emissions.

The relative lack of past interest from industry in investing directly in such a potentially valuable technology is difficult to define, but may well be related to the uncertainty generated by the predominance of expertise developed in the FSU, with associated perceptions in relation to economic viability and environmental issues.

Successful application of the UCG process requires the integration of a wide range of technical disciplines, which may also explain its slow commercial acceptance. Such specialist skills as are used in the fields of chemistry, chemical engineering, geology, geotechnical engineering and geohydrology are all necessary to plan and execute a successful UCG project.

Despite the rapid growth of interest in the development of commercial projects using UCG technology to fuel a combined cycle plant for power generation, the fact remains that no such project currently exists. There are a number of factors that impact on the conversion of a successful pilot burn into a commercially viable project.

The first and most obvious is the economics of the project, which must be assessed from projections rather than from a body of past experience. In reviewing results from the pilot burn at Chinchilla, Walker *et al.*[10] estimated that the cost of power production using UCG gas in association with a combined cycle power plant was about 1·5 US c/kWh, compared with a price of more than 4 US c/kWh using surface gasification of coal. While these costs of production will have varied over time, two conclusions from the work appear to be still valid—firstly, the cost of power using gas from UCG operations will be substantially cheaper than that produced from surface integrated gasification combined cycle (IGCC) plants; secondly, UCG power production costs are competitive with the most economical coal-fired power plants.

Even with projected economic viability, there are a number of other factors that impact on the decision by any debt or equity financier to fund a future proposed UCG–IGCC project. These include

(*a*) acceptance of the credibility of proposed UCG technology
(*b*) detailed design of gas clean-up plant to meet environmental standards for both gas and liquid emissions
(*c*) sufficient gas production from a pilot burn to satisfy concerns about gas composition, its variability and continuity of production
(*d*) gas transportation requirements to the end user
(*e*) environmental issues, including rehabilitation
(*f*) project risk assessment
(*g*) need for independent reviews to support financing decisions and the shortage of relevant international experience to undertake this work
(*h*) need to meet required project financial returns.

Most of the above must be considered in the development of any commercial infrastructure project. Of particular relevance to UCG projects is the uncertainty associated with what is perceived to be a new technology. With respect to environmental issues, the success of the RM1 and Chinchilla projects, which both received formal environmental permission, provides relevant background evidence to support proposed new projects, although each approval agency will require a significant period of familiarisation with the technology before issuing appropriate permits.

UCG technology has a long history in a number of countries and in each there have been early trials undertaken that have had some environmental impact, and led to modification of operating techniques and emphasis on the importance of a thorough site characterisation programme as a basis for process design. It is clear that any successful commercial project requires that both the supplier of the UCG technology and operator of the UCG gas field have a breadth of experience to ensure that mistakes made in past trials are not translated into future commercial operations. The limited availability of such expertise world-wide will largely control the rate of acceptance of the technology into mainstream energy supplies.

It is the current author's view that commercial UCG gas production from a number of projects will be in progress within the next five years. This view is supported, not just by the breadth of projects in progress or under current consideration, but also by the fact that they are being put together by both large and small companies with quite different risk profiles towards new technology. When this occurs, UCG technology will then have taken its place in the spectrum of energy sources available to industry.

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