COALTECH 2020

Task 1.3

Unconventional extraction methods to harness the energy and carbon in coal

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Executive summary

In South Africa, coal accounts for about 75% of the country's primary energy supply. As a non-renewable resource, there is an increased need for sustaining the coal reserves. Some South African coal resources are unminable due to various reasons, including being at too a great depth to be economically mined or of too low rank to be utilized. Thus, technologies (Table 1) that can be utilized for extracting currently unminable *in situ* coal are important in extending the life of the coal reserves.

A desktop study has been undertaken to assess the current status of known technologies that can harness the energy and carbon in coal. Information was gathered by reviewing existing literature, internet searches and consultation with industry experts involved with these technologies. This desktop study concentrates on various technologies that can be used or applied to unminable *in situ* coal, thus extending the life of the existing coal resources. The current status of the applicability of various technologies to South Africa is also discussed.

Underground coal gasification (UCG) has been researched internationally for a long time but there are still major technical difficulties. UCG is not fully established yet due to the complexity of reaction kinetics, heat transfer and gas flow in the reservoir model. The problems are further complicated by the fact that these technical difficulties are site specific and will vary from each coal basin depending on the coal characteristics.

Like UCG, coal bed methane (CBM) and coal mine methane (CMM) drainage provide possible exploitation of the coal resource in areas where the coal would be unlikely to be mined using traditional mining methods. CBM and CMM have been commercially applied in various countries. CMM drainage also has the advantage that it enhances mine safety ahead of mining. Major geotechnical barriers such as low permeability of coal, variable or low quality gas and variation in gas supply hinder the development of CBM and CMM drainage.

The biotechnology process in coal is promising but extensive research is still required. Thus progress needs to be monitored, as it might lead to the utilization of low rank coal, which is usually not mined or discarded. This will consequently increase coal resources. Borehole mining has not been proven in the coal industry and appears to be inapplicable to South African coal, which is shallow and not steeply dipping, indicating that open cast mining might be cheaper.

Anglo Coal is currently investigating CBM in the Waterberg Coalfield; and the Department of Minerals and Energy with external agencies in the Springbok Flats Coalfield, South Africa. ESKOM is busy with a scoping study on the application of UCG in South Africa. These feasibility studies are still in the early stages and if they are successful, the life of the coal resources in South Africa will be increased substantially. CMM drainage has been attempted in the past at Majuba Colliery but was discontinued when the mine was closed due to structural complexity. It is thus recommended that CMM drainage, CBM and UCG be investigated at Majuba Colliery as the structural complexity will not be crucial as there will be no need to mine the coal.

Table 1: The summary of techniques considered

Technology	Status	Benefits	Major Potential Barriers	Status in South Africa
Underground Coal Gasification (UCG)	• Mature- researched for over 50years. • Commercially applied in Australia, U.S.A., CIS and UK.	• Extraction of otherwise unminable coal.	• Complexity of UCG technical model esp. reaction kinetics, heat transfer and gas flow are site specific.	• Conceptual study to apply UCG locally by ESKOM is ongoing.
Degasification (Coal Mine Methane (CMM))	• Mature - applied commercially in the U.S.A., UK, Australia, China, CIS, and Germany.	• Extraction of gas in otherwise unminable coal. • Increases safety in mining environment.	• The gas might be of very low quality and enrichment might be necessary. • Very low concentration of gas in coal.	• Currently not applied locally but was attempted at Majuba Colliery before it was closed.
Coal Bed Methane (CBM)	• Applied commercially in Belgium, CIS, Australia, USA and China.	• Extraction of gas in otherwise unminable coal. • No surface subsidence.	• Technical barriers i.e. low permeability of coal, variable or low quality gas and variation in gas supply. • Lack of infrastructure.	• Feasibility study in the Springbok Flats Coalfield.
Biotechnology	• Still in the early stages of research done by the Brookhaven National Laboratory.	• Utilization of very low rank coal, which is often discarded.	• Reaction kinetics and mechanism not yet fully understood.	• Still far from implementation stages.
Borehole Mining	• Currently applied in mining salt or phosphate and uranium ore. • Successfully applied in mining of frozen gold placers in Alaska.	• Potentially low mining costs. • Highly automated and not labour intensive.	• Has not been proven to be efficient and economical in coal mining. • Large diameter holes might be expensive in some areas	• Not tested locally especially in coal mining.

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Introduction

South Africa is the world's fifth largest coal producer and second largest coal exporter. Prior to the early 1990s, the country developed a strong reliance on coal as an alternative to imported oil because of sanctions. Today, coal accounts for about 75% of the country's primary energy supply, one of the highest percentages worldwide. As a non-renewable resource, there is an increased need for sustaining the coal reserves. Some South African coal resources are unminable due various reasons including being at too great a depth to be economically mined or of too low rank to be utilized. Thus technologies that can utilize unminable *in situ* coal are important in extending the life of the coal reserves.

The aim of this desktop study is to assess the current status of the known technologies that can be utilized to harness the energy associated with carbon in coal.

Inseam gasification/Underground Coal Gasification (UCG)

General description

UCG is an *in situ* combustion technique that converts coal underground, into a combustible gas, thus providing a clean and convenient source of energy from coal seams where traditional extraction methods are economically, environmentally or technically not appropriate (e.g. in areas where coal seams are at great depth). It is applicable to coal seams that are more than 3m thick. The gas is suitable for industrial heating, power generation or hydrogen and natural gas production (Walker, 1999; Coal-ucg, 2002; Green and Armitage, 2001).

There has been a great improvement in the techniques used with each stage of development and in assessing resources that can be feasibly extracted using UCG. Numerous techniques are used for UCG operations. A Soviet technique is commonly applied and employs a regularly spaced set of vertically drilled holes, with 10 to 15m spacing dependent on the coal permeability. The holes are linked by hydrofracturing and burning between the holes. Burning starts from one row of holes towards another parallel row forming a gasification front. Additional rows of holes are brought into operation as required (Beath *et al*., 2001). The controlled retracting injection point (CRIP) method has been used in trials in the USA and Western European. It involves the drilling of an injection pipe inside the coal seam such that it initially ends close to the vertically drilled production hole. As the coal is consumed between the two holes, the distance between them is increased by destroying a section of the injection pipe to make a new injection point. This is repeated as many times as possible depending on the length of the injection pipe. The technique used by the British in the 1950s is currently used by the Chinese and it involves gasifying between mined tunnels linked by drill holes. (Beath *et al*., 2001).

Current Status

The in-seam gasification of coal has been an objective of coal research since the early UK experiments in Durham in the early 1920's and trials were started in earnest in the former Soviet Union in the 1930's. These continued at a high level of activity after the Second World War and the trials established the basic technology of UCG. The UCG technology has been in a mature, development phase in various countries, with research done over the past 50 years. It has had several different stages of development worldwide (Coal-ucg, 2002).

Commonwealth of Independent States (CIS)
The Soviet Union has had a series of commercial scale sites since the 1930s. A number of commercial sized schemes were initiated in the Soviet Republics, most notably in Russia and Uzbekistan. At least one commercial scale plant in Uzbekistan has been operational since the 1930's.

European Union
Significantly sized operations are present in the United Kingdom. The recent UCG trial in Spain, between 1992 and 1999, has demonstrated the technical feasibility of UCG in typical European coal seams and the UK Department of Trade and Industry is now undertaking a UCG study programme with industry to critically assess the commercial feasibility of UCG (Beath *et al*., 2001; Green and Armitage, 2001).

Australia
A demonstration plant in Australia has been operating for two years (Walker, 1999; Beath *et al*., 2001; Green and Armitage, 2001). A UCG project in Chinchilla, Queensland, Australia has been operational since 1999 and has been in continuous production for 21 months by October 2001 (Walker *et al*., 2001).

South Africa
ESKOM is in the early stages of a conceptual study of applying UCG locally. The study will involve assessment of local sites, environmental impact, technology, geology and costs. One of the potential sites is the Waterberg Coalfield in the Northern Province where the coal seams are at uneconomic depths. Perceived problems in South African context are that most coal seams are thin and are at shallow depths (Van der Riet and Dempers, 2002).

Others
There have been extensive trials in the USA in the 1970s in Canada, New Zealand, China and Western Europe in the last decade.

Benefits
The UCG has been supported as a coal extraction technology due to the following reasons:

a) Extraction of coal that would otherwise be unminable, e.g. deeper seams
b) Reduced capital expenditure on coal processing plant.
c) Lower environmental impact than other coal mining/utilization processes.
d) Improved drilling techniques allow for reduced costs and access to larger coal volumes.
e) No ash or coal handling at the surface.
f) CO_2 can be readily removed from the product stream, thus producing a source of clean energy with minimal greenhouse gas emissions.

Potential Barriers
Investors have been reluctant in adopting the UCG technology due to the following (Beath *et al*., 2001; Green and Armitage, 2001):

a) Uncertainty of the operations.
b) Some techniques developed and tested on a large scale, especially in the USSR, are generally suitable for shallow coal seams only.
c) The CRIP technique is suitable for deeper seams but has not been tested on a large scale.

d) Tests done on the CRIP technique involved an in-seam length of the injection pipe that rarely exceeded 100m in length whereas a commercial operation would require in-seam lengths of up to 1km and the stability of the gasification is unproven for this length of seam.
e) Difficulty in understanding the complex model of the UCG operation especially the reaction kinetics, heat transfer and gas flow, because the reaction container is not well defined i.e. the container reacts, is subject to breakage and leakage of both gas outwards and inwards, is of inconsistent shape and changes size.

Issues regarding protection of underground acquifers, adequate depth to avoid surface disruption and environmental impact assessment and analysis have also not been adequately addressed.

Coal Bed Methane (CBM)

General description
Coal Bed Methane (CBM) is a natural gas (methane) formed during coalification and only a fraction of this remains trapped under pressure in the coal seam and surrounding rock. It is not an integral part of the coal, but exists as a gaseous phase trapped in cleats, fractures and other spaces within the coal. The amount of trapped methane depends on coal rank and coal seam depth. As the coal rank increases, the amount of methane also increases. Pressure increases with depth and the adsorption capacity of coal increases with pressure. Thus the deeper coal seams generally contain more methane than shallow seams of the same rank. Methane can be released to the atmosphere from near surface coal seams through natural fractures in the overburden strata (Irving and Tailakov, 2000). CBM is recovered from virgin coal by releasing the gas located both within the coal and adsorbed onto the surface of the coal. Coal seams are injected with a high pressure water, foam and sand mix. The high pressure fractures the coal for some distance around the borehole. The sand holds the fractures open, enabling the water and gas to flow to the well bore and hence to the surface. CBM offers a method of extracting methane from unworked coal without detrimentally affecting the physical properties of the coal (USEPA, 1998).

Current status
There has been a recent growth in CBM development in the U.S.A. and elsewhere in the world and there is a growing recognition of CBM as a valuable resource, resulting in efforts to characterize and assess potentially productive areas.

Commonwealth of Independent States (CIS)
CBM resource assessment has been underway for over a decade in Ukraine and a CBM and CMM production target of 8 billion m^3 by 2010 has been set by the Alternative Fuels Resource Center. A CBM Drilling Pilot Program is coordinating and demonstrating the feasibility of drilling CBM drainage wells in advance mining. In Russia, a feasibility study of CBM in Kuzbass, funded by the Russian government and the United Nations Development Programme, focused on the CBM projects at selected mines. The project started in January 2000 (USEPA, 1999).

Belgium
Engineers in Belgium are investigating opportunities for classical CBM production together with the possible CO_2-enhanced production to be injected into the coal seam thus liberating adsorbed methane (USEPA, 2000a).

China
China has an estimated 14 trillion m^3 of exploitable CBM reserves primarily distributed in eight areas. More than 100 exploration boreholes well have been drilled. Geological conditions i.e. low permeability has rendered many of these unsuccessful (USEPA, 2000a).

Southern Africa
In 2001, CBM development was attempted in Zimbabwe but was later suspended (Geocities, 2002).

South Africa contains the seventh largest coal reserves in the world and thus CBM could become a viable and profitable energy source for South Africa and could forestall the future need to import natural gas. Evidence of the gas potential arises from a long record of gas-related mine explosions (World Bank and USEPA, 1998), including three major disasters in 1980's (Bibler, 1998).

AngloCoal is currently busy with a feasibility study of CBM in the Waterberg Coalfield and five spot pilot tests are underway. There are no major problems with geology, as it is well understood, however there are reservoir engineering problems. These relate to the fact that oil well technology used still need to be modified and adapted for gas characteristics (Dowling, 2002).

A pre-feasibility study in Springbok Flats Coalfield was completed in January 1996. This involved the Department of Minerals and Energy, Southern African Development Community, U.S. Trade and Development Agency, U.S. Department of Energy, Natural Buttes Gas Corporation and Advanced Resources International (World Bank and USEPA, 1998).

The pre-feasibility study analysis indicated a potential methane production of 0.7 million m^3 which could be absorbed by markets in the immediate vicinity. Based on these conclusions, a recommendation was made to proceed with a budgeted risk-managed exploration program to confirm the production potential through exploratory drilling and to quantify the risk potential through *in situ* gas recovery parameter evaluation (World Bank and USEPA, 1998).

The feasibility study and preliminary drilling has not yet been completed. The feasibility study includes the geotechnical assessment of the extent of the CBM resources, determination of economic recovery including pilot production, a detailed inventory of possible natural gas markets and applicable gas pricing, and a detailed economic analysis of all aspects of the project. The study would include an environmental impact assessment that would encompass an evaluation of the benefit of natural gas substitution for coal and firewood heat energy. There is a potential for recovery of potable water for household and agricultural use, which can be produced in conjunction with the CBM recovery process (World Bank and USEPA, 1998).

Benefits
CBM provides the following benefits:

a) It facilitates exploitation of the coal resource in areas where the coal would be unlikely to be worked by traditional mining methods.
b) Very little or no surface subsidence as the coal remains in the ground.

c) It can facilitate extraction of gas from coal seams prior to mining the coal, thus reducing the potentially dangerous methane gas prior to carrying out traditional mining methods and, thus, maximizing revenue from coal.
d) Methane quality is such that it has the potential to be fed directly into the gas distribution network as it has a lower carbon dioxide content.

Potential Barriers

a) In South Africa, Minerals Act, 1991, CBM is defined under law as a mineral in its own right, therefore, two companies can have rights to a gassy seam—one for coal and one for methane, thus causing ownership problems.
b) Ownership rights have not yet been determined especially in abandoned mines.
c) “Ringfencing” in South Africa: Treatment of development costs, which preclude the write-off of development costs against other income.
d) Technical/geological barriers i.e. low permeability of coal, variable or low quality gas, variation in gas supply.
e) Economic and institutional barriers, pertaining to the information pertinent to development of the resource, lack of infrastructure, lack of capital and low natural gas prices.

Degasification/Coal Mine Methane (CMM)

General description

Coal mining releases methane from the coal and adjacent rock. Coal mine methane is produced as a result of the fracturing of coal and coal measures strata as part of historical and current mining operations, releasing the methane, which had been adsorbed within it. Because methane is explosive in air in concentrations ranging from 5 to 15 percent, safety requires removal of methane released during mining. Gassy mine operations employ large ventilation systems to draw clean air into and through the mine to dilute and remove methane and sometimes must supplement their ventilation systems with methane drainage systems (USEPA, 1998).

One or more of the following methods, commonly called degasification systems, are used to drain methane from coal (USEPA, 1998).

a) Pre-mine boreholes, drilled from the surface, drain coalbed methane from unmined areas, either years in advance of mining operations, or from coal seams that will never be mined. Drained gas contains more than 90% methane and can be injected directly into natural gas pipelines.
b) Gob boreholes, drilled from the surface, drain coal mine methane from gob areas (a gob is the fractured zone caused by collapse of the strata around the coal seam after mining) and drain gas contains 30% to 80% methane, which declines in quality over time.
c) Horizontal boreholes, drilled inside the mine, drain methane before mining.

Current status

Commercial exploitation of CMM has a well proven potential of harnessing the gas safely and beneficially to generate electricity or produce steam.

United States of America

17 CMM pipeline sale projects were active in the U.S.A. as of January 2000. United States coal mines produce more than 4.2 billion m^3 of coal mine methane each year. Of this, mines recover nearly 4.2 m^3 for use as fuel, primarily for sale to pipeline companies. In 1999, over 85% of methane produced from coal mines degasification systems was captured and utilized compared to only 25% in 1990 (USEPA, 2000a).

United Kingdom (UK)
Large scale methane drainage and utilization in Britain began in the 1950's. By mid-1960's mine gas utilization was well established at numerous mines. The largest coal mine methane-fueled turbine in Europe is at Harthworth Colliery in Nottinghamshire. Recovery and use of coal mine methane has been restricted by low permeability of the coal, low gas pressures and difficulty in using horizontal in-seam boreholes to recover methane (Bibler *et al*., 1998).

Commonwealth of Independent States
5 coal basins have been identified in the CIS where there is potential for CBM and CMM development. Of the five basins, the Donetsk and Kuznetsk Coal Basin (Kuzbass) in Russia has a great potential for CBM development provided technical, financial and greenhouse gas accounting barriers are removed (USEPA, 2000b).

Australia
A successful CMM pilot project has been conducted in Australia by BHP (USEPA, 2002). At Appin Colliery, Australia, Ventilation Air Methane (VAM) from a ventilation shaft was used as a supplemental fuel and supplied about 7% of energy (Schultz, 2001).

China
China has a long history of coal mine methane drainage. China constitutes 41% of the global CMM emissions and is the highest in the world (USEPA, 1999), because of the great depth and high rank of China's coal (Bibler *et al*., 1998). About 131 state-owned mines currently have methane drainage systems. The United States Environmental Protection Agency (USEPA) and the State Administration of Coal Safety Supervision of China have identified eight coal mining areas (Jincheng, Huainan, Huaibei, Panjiang, Pingdingshan, Fushun, Yangquan and Jiaozuo) that are favorable in terms of CMM/CBM resource and market potential (Schultz *et al*., 2001; Schultz, 2002).

Germany
An estimated 1.8 X 10^6 m^3 of methane are liberated annually from underground activities, of which only 30 % are drained (Bibler *et al*., 1998). 71% of the drained methane is used for power generation and heating. It is estimated that as much as 45% of emitted methane from coal mining activities could be drained. The main barrier in recovery is low concentrations of methane in gas mixture and the fact that safety regulations in Germany prohibit any utilization if methane is less than 25%.

India and Japan
A demonstration project is underway in India and Japan is experiencing obstacles regarding the lack of transmission lines, low electricity prices and high drilling costs (USEPA, 2000a).

South Africa
There is estimated 1.1 x 10^6 m^3 methane liberated by underground mining activities annually (Bibler, 1998). There is no active coal mine methane recovery and end-use activities in South Africa. However in the gold mining sector, methane coming from the mine shafts for over 20 years has been utilized to fuel kitchen stoves and bath

houses. South African coal seams are relatively shallow and are generally not regarded as being very gassy. Thus, little attention has been paid to coal mine methane recovery and end-use. Several individual examples of gassy mines in South Africa, like the Majuba Colliery, experience higher than expected levels of methane in the mine workings. Gas desorption tests showed the coal to contain up to 8.5 m^3/ton. In the early 1990s several in-mine horizontal wells were drilled to degasify the coal in advance of mining. The mine operators at Majuba Colliery were contemplating various coal mine methane drainage and end-use scenarios, but the mine was eventually closed due to structural complexity (Bibler, 1998).

Benefits

a) Reduces an uncontrolled danger and potential surface hazard to individuals and property
b) Improves safety conditions for miners.
c) Reduces harmful ventilation of a greenhouse gas to the atmosphere.
d) Can be used to generate electricity, as fuel for local use in heating and cooking, as fuel for co-firing boilers or as industrial feedstock purposes.
e) Can be used for injection in blast furnaces, in fuel cells and in methanol production etc.

Potential Barriers

a) Low- to medium-quality gas is difficult to market.
b) Uncertainty surrounding the ownership of CMM has hindered development in some countries.
c) Insufficient reliable storage facilities in mines that are far from the gas stream network.
d) Retrieved gas in CMM may still require processing (initial enrichment with propane) prior to its injection to gas stream.

Extraction of *in situ* carbon and hydrocarbon compounds

In situ hydrocarbon recovery from coal beds consists of heating the coal seam with one or more heat sources. The heat from the heat sources, to selected sections of the seam, is controlled such that an average temperature of < 375 °C is maintained throughout a majority of the sections of the formation, producing hydrocarbon liquids and gases. The superposition of two or more heat sources result in pyrolysis of some of the hydrocarbons within the coal seam. Suitable heat sources include electric heaters, surface burners, flameless distributed combustors, and natural distributed combustors (Berchenko *et al*., 2002;).

The pressure of the gas liberated is controlled as a function of applied temperature, or the temperature is controlled as a function of pressure, especially by valves coupled to one of the heat sources or coupled to the production well, such that the average heating rate in the formation is < l°/day during pyrolysis. The process, which can also be used for hydrocarbon recovery from petroleum reservoirs and oil shale beds, can be modified for recovery and treatment of products more typical of coal processing (e.g. ammonia, H_2S, aromatic hydrocarbons, pyrolysed tars, etc.) (Berchenko *et al*., 2002; Wellington, 2002).

Application to South Africa

In-situ hydrocarbon recovery can be applied in both coal and oil shales. Oil shale deposits, in the form of torbanites, occur towards the top of the Vryheid Formation and are associated with the No. 5 Seam. Torbanites are black to greenish-black oil shales that contain up to 90% by volume of telalginite. Oil yields of these torbanite range between 140 and 800 l/t and depends on the grade and degree of maturation. However these are relatively thin (less than 1.2m thick) and are of restricted areal extent, rarely exceeding 25-100 km^2 (Cadle *et al*., 1993).

Biotechnology in coal

General description:
A process of microbiological desulphurization has been applied for quality improvement of coals used as a fuel or raw material in the chemical industry. Biological desulphurization reactions affect inorganic substances in coal. However, this process can affect also organic matter of coal. This is not only beneficial for some coal properties, like content of sulphur, which is hazardous to the environment, but can also, improve the coal characteristics. The microbes break down the low-rank coal's complex molecules to form simpler into more easily combustible compounds. Thus, converting ordinary coal to an environmentally friendly attractive resource by removing sulphur and heavy metal contaminants.

Current Status
The process is still in the research stages. The Brookhaven National Laboratory is conducting research into this area as an assessment of these accessory alterations of the organic matter in coal. This could help to better understand the reaction mechanisms and could aid in the increase in the quality of these processes, such as finding conditions that are more suitable for complete alteration of desulphurized bituminous coals (Brookhaven, 2002). The research is still in the early stages of laboratory research. According to Lin (2002), progress is slow, however, the results are promising and they are looking for funding from US Department of Energy and foreign companies as well.

Benefits
The benefit of this technique will be in the use of large resources of low rank coal, which are presently not used or mined, thus leading to the extension of the life of the coal reserves.

Potential Barriers
At the moment the technique is applied to coal slurry, thus *in situ* application will be more difficult in terms of constraining microorganisms to a specific seam or area for optimal performance.

Lin (2002) is recommended as contact person for additional information on this topic.

Unidentified technologies and further research

Borehole Mining
Traditionally, borehole mining involved drilling of a borehole from the surface into the coal seam. A high pressure water jet is then used to loosen the coal, which is pumped to the surface with the water. Settling tanks are used to recover water from the coal slurry to be used again (Niosh, 1977; Simonis, 2000).

A modified method includes drilling of at least two vertical boreholes in a coal seam. High pressure water jet is used to erode coal between the boreholes, with one borehole used as an injection well and the other dedicated to pumping out coal slurry.

A modified method of borehole mining used in UCG involves two vertical boreholes and a connecting channel between boreholes. Ignition and gasification of the coal mass occurs in channels, with the supply to the underground gas generator through one of boreholes, and withdrawal of formed gas through the other borehole. The benefit of this methodology has been an increased calorific power of produced gas (Kondyrev *et al*., 2002).

Some commodities, such as salt or phosphate and uranium ore, are mined through borehole mining and it has been used with success in mining of frozen gold placers in Alaska in the early 1990s (Niosh, 1997).

Benefits

a) Suitable for steeply dipping coal seams.
b) Highly automated and not labour intensive.
c) Lower mining costs.
d) Undisturbed overburden, thus minimal environmental impact.
e) Fragmentation and material transport system incorporated into a single device.
f) No health and safety problems as no men or materials are placed underground.

Potential Barriers

a) The use of borehole mining has not been proven to be efficient and economical in coal mining.
b) Drilling large diameter holes might prove to be expensive in some areas.

Conclusions

UCG has been researched for a long time but major technical barriers still exist. Technical barriers regarding the complex model of the UCG operation especially the reaction kinetics, heat transfer, gas flow need to be well addressed before any attempt at UCG is undertaken. This is also complicated by the fact that these barriers will vary from one coal basin to another and are thus site specific.

The introduction of tax incentives (tax relief) and credit system associated with development of CMM and CBM has promoted the beneficial capture and use in various overseas countries like West Virginia and has set an example for other countries to follow suit. The Bill provides for an exemption from the tax levied upon everyone involved in CBM/CMM for sale, profit or for commercial use (USEPA, 2000a). This is in line with the recognition that mine safety is enhanced and greenhouse gas emissions are reduced in the process (USEPA, 2001). International adoption of a tradable permit system for methane emission would also encourage CBM and CMM recovery and use (Bibler *et al*., 1998).

Barriers such as unresolved legal issues concerning ownership in CBM and CMM, a lack of information on profitability capital and other technical issues, need to be addressed, for beneficial development of these technologies. Very low concentrations of methane can permanently hinder CBM and CMM recovery. It is recommended that Majuba Colliery be used as a test site for UCG, CBM and CMM drainage as faulting associated with the structural complexity will be advantageous for these technologies. The extent and resources of the torbanite deposits, associated with the No. 5 Seam towards the top of the Vryheid Formation, should be assessed to determine whether *in situ* hydrocarbon extraction would be economically viable.

There is still a long way to go with the research in the biotechnology process but must be monitored for progress as it might increase the coal resources by utilizing low rank coal, which would have been discarded. Borehole mining has not been proven in coal industry and appears to be inapplicable to South African coal as they are much shallower and not steeply dipping, thus opencast mining might be cheaper.

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