STUDY OF UNDERGROUND COAL GASIFICATION

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ABSTRACT
The underground coal gasification (UCG) technology converts coal into product gas and provides the option of environmentally and economically attractive coal mining. Obtained syngas can be used for heating, electricity, or chemical production. Numerous laboratory coal gasification trials have been performed in the academic and industrial fields. Lab-scale tests can provide insight into the processes involved with UCG. Many tests with UCG have been performed on ex situ reactors, where different UCG techniques, the effect of gasification agents, their flow rates, pressures, and various control mechanisms to improve gasification efficiency and syngas production have been investigated. This provides an overview of recent research on UCG performed on a lab scale. The study focuses on UCG control variables and their optimization, the effect of gasification agents and operating pressure, and it discusses results from the gasification of various lignite and hard coals and environmental risks of UCG.

Keywords: Underground Coal Gasification (UCG); Coal Mining; Green Coal Mining.

1. INTRODUCTION
The concept of underground coal gasification (UCG) is simple. It involves reacting (burning) coal in situ/in-seam, using a mixture of air/oxygen, possibly with some steam, to produce a syngas. The steam may come from water which leaks into the underground cavity, from water already in the coal seam or from steam deliberately injected. Some coal combustion takes place generating enough heat to support the process reactions. Then gasification takes place at the elevated temperatures with a stoichiometric shortage of oxygen involving the partial oxidation of coal, so the principal gases formed are hydrogen and carbon monoxide.

However, there are many other products, including carbon dioxide; hydrocarbons such as methane; tars; and compounds such as hydrogen sulphide and carbonyl sulphide (COS) arising from impurities in the coal. The product mix can vary widely depending on a number of factors. If the oxidant is air, there will be significant amounts of nitrogen present.

The syngas produced is cleaned, and can be used to produce electric power or as a chemicals/liquid fuels feedstock. If air is used as the oxidant, the syngas has a heating value which is about one-eighth that of natural gas while if oxygen injection is used then it is about one quarter to one third. UCG offers the potential for using the energy stored in coal in an economic and environmentally sensitive way, particularly from deposits which are un mineable by conventional methods. If UCG were to be successfully developed and widely deployed, then the world's coal reserves might be revised upwards by a substantial amount. Site selection of the places where UCG could be carried out is critical to any development since the geology must be appropriate.

The main method of achieving UCG involves a minimum of two boreholes (or wells) drilled into the coal seam some distance apart, and connected by a link/channel through which gases can flow. These holes may be vertical, or they can be inclined boreholes, partly drilled through the coal seam. One of the holes, referred to as the injection borehole, is used to supply the gasifying agent (air, oxygen enriched air, or oxygen, possibly with added steam).

The other is the production borehole (or well) through which the product gases are carried to the surface for treatment and use. With some production patterns the function of these wells is interchangeable, and from time to time, the supply/injection well becomes the production well, and vice versa. This may be to achieve the linkage between them, or to smooth out the pattern of gasification in the (constantly changing) underground gasification chamber. Commercial-scale operations using UCG would involve multiple boreholes/wells to produce sufficient quantities of syngas, based around the two wells concept described above.

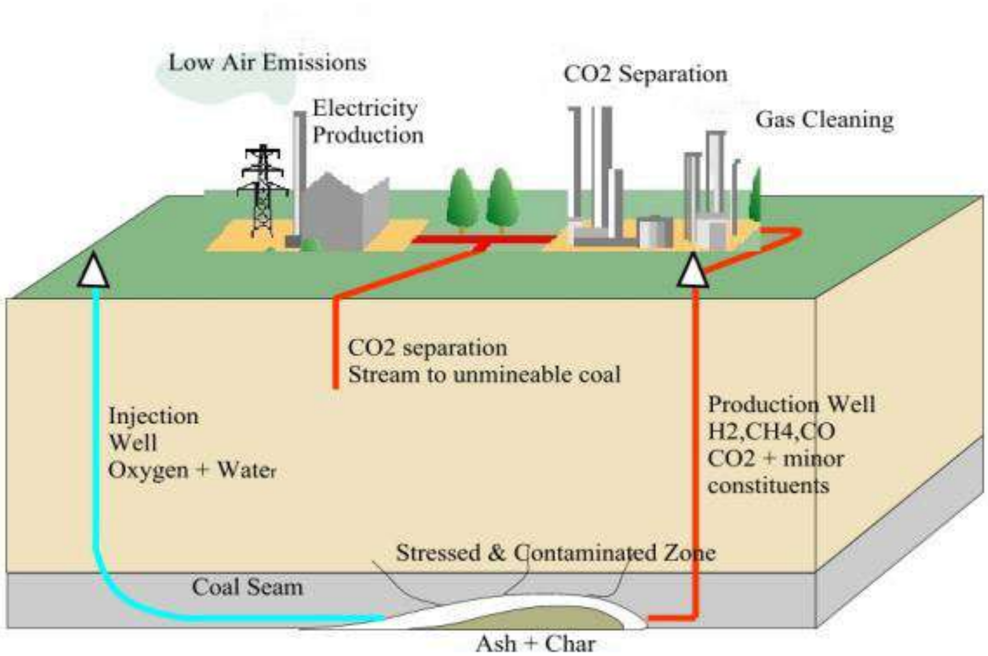

Figure 1: Schematic of the components of the UCG process collocated with electricity generation (UCG Engineering, Ltd., 2006)

2. SURFACE REQUIREMENTS

UCG activities can result in surface subsidence, and this effect may restrict the number of places where it will be practical to carry it out. Subsidence is generally a very gradual process, typically only involving a few centimetres in a year, and is dependent on the depth and thickness of the coal seam, on the amount of coal extracted, and on the nature of the overlying strata. UCG will generally best be undertaken where the land (on the surface) is fairly open, undeveloped and of relatively low value.

Using some UCG methods, the landscape will be punctured by a whole network of boreholes which are moved progressively across the surface as gasification of the underground seam proceeds. Other methods using inclined and in-seam boreholes should be less intrusive in terms of the pipework infrastructure, but subsidence effects will be much the same.

All developments will require the provision of surface installations to supply the feed gases (including possibly oxygen and steam), to facilitate ignition of the underground seam, and to clean and use the syngas produced (either for power generation or chemicals/liquid fuels production). Developments will also require appropriate administration and laboratory buildings.

The product gas from UCG can be used in a variety of ways, including

- Combustion in a gas turbine connected to an electric generator. The hot gas from the turbine can be used to make steam, which in turn can be used to drive a steam turbine or steam engine, connected to an electric generator;
- Combustion in a boiler to make steam which can drive a steam turbine or a steam engine connected to an electric generator;

- Direct feed to a fuel cell that can tolerate carbon monoxide to generate low voltage electrical current, which can be stepped up and fed to a power grid;
- The gas can be "shifted" to make a mixture of hydrogen and carbon dioxide, with very low levels of carbon monoxide, and then fed to a low-temperature fuel cell to generate low voltage current;
- Used as a chemical feedstock to produce methanol, or a variety of other chemicals via Fischer Tropsch processes.

3. COAL SEAM PROPERTIES AFFECTING UCG

While the coal seam properties are important, as can be seen from the list below, it is the geological setting which determines the potential application of UCG, and this is discussed further in Section 2.3.6. Key features which affect the use of UCG are:

- The geological structures both above and below the coal seam. Particularly the properties of the roof materials above the seam, and of the hydrogeology of the area. If there is an impermeable seal between the coal seam and the surface, then the environmental implications are very different compared with those for a roof consisting of permeable shales or sandstones;
- The amount of water available long-term to provide a seal around the reactor cavities to minimise the risk of gas escape, where this is necessary;
- The deposit/seam depth, thickness and inclination;
- Seam continuity and its physical strength;
- The nature of the coal (and in particular its rank and reactivity, together with its ash, moisture, sulphur and methane contents);
- The permeability of the seams, based on the pore structure and the presence of cleats (or cracks). In addition, the presence of fracture planes or shear zones in or near the seam is of significance as these might provide leakage paths for the syngas formed;
- An UCG activity expects some goafing (collapse) of the immediate overlying strata into the cavities created during gasification, and planning this forms part of the process. The extent and nature of subsidence through to the surface depends on the nature of the overlying strata and varies from site to site;
- Most of the ash in the coal remains underground and acts as a buffer to reduce subsidence developments on the surface. UCG requires a largely temporary infrastructure of wellheads and pipelines on the surface. A power generation unit and/or chemicals production facility to clean and use the syngas would occupy a relatively small area, but would be there for the life of the project, which might be 20 to 30 years. Carrying out UCG will be much easier under land which is undeveloped and where a small amount of subsidence is likely to be acceptable. It may also prove to be possible to recover energy from coal resources under the sea.

4. OBJECTIVE OF UCG

As one of the technologies for coal development, underground coal gasification (UCG) technology is an industrial process which converts coal into product gas through thermal and chemical action of coal for clean development and utilization of coal.

5. UCG CHEMISTRY

During gasification, the in-seam coal is heated by hot gases to a very high temperature and is consumed by oxidation reactions. Then in a region where the oxygen content is depleted, the gasification reactions take place. A flame front is initiated within the passage linking the injection and production wells, and as the gases pass through the various reactions approach equlibrium conditions before they leave via the production well at temperatures which will probably be between 200ºC and 400ºC.

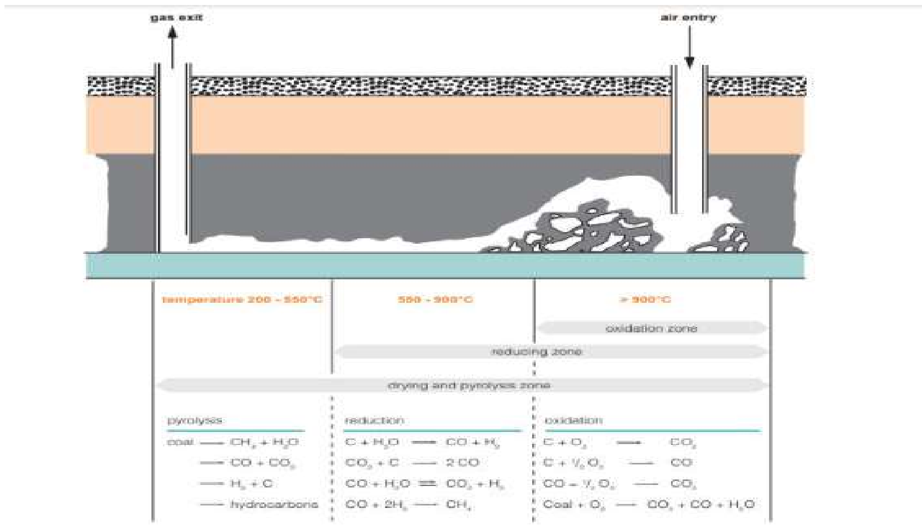

Fig 2: Schematic of the processes involved in UCG

Fig. is a schematic showing the various reactions taking place using the basic Russian methodology, with linked vertical wells (LVWs). As the coal is heated (throughout the length of the combustion/gasification cavity and the linkage routes), the coal starts to lose the moisture held in the pore structure, and then undergoes pyrolysis at temperatures above 400ºC, during which hydrogen-rich volatile matter is released, together with tars, phenols and hydrocarbon gases. Simultaneously, at higher temperatures, the char is gasified, releasing gases, tar vapors and solid residues.

6. Global Experience in Coal Gasification

Global coal gasification market is expected to reach around 3,89,825 MW by 2026, growing at a CAGR of approximately 10.8%.5 Fertilizer segment is anticipated to hold the major market share. Ammonia production by coal gasification has increased the demand for fertilizers. Another segment with a good growth rate, above 10.5%, is power generation. Growing trend of Integrated Coal Gasification Combined Cycle (IGCC) power plants worldwide has increased the opportunities. Demand for coal gasification technology has increased in fuel gas production, owing to the increased use of synthetic natural gas. By region, the global coal gasification market is segmented into North America, Asia Pacific, Europe, Latin America, and the Middle East and Africa.

a) Region dominating the coal gasification market is Asia Pacific. China contributed the highest market share in 2017. Other countries, such as India and Japan, are also promising markets for coal gasification.

b) North America is likely to show a good rate of growth. The U.S. contributed the majority market share in the year 2017.

c) Moderate market growth is likely to be registered in the European region. Germany contributed the majority share in 2017.

d) The Middle East and Africa and Latin America are likely to witness good market growth

6.1 CHINA

The Chinese government's initiatives in its 11th and 12th five-year plans have boosted the gasification industry in the country. China produces more than 90% of its ammonia through coal gasification. China is expected to increase the uptake of large-scale coal-to-SNG projects and possibly scale up various coal-to-oil technologies projects, which in turn, would supplement the gasification market.

a. The coal chemical industry, which includes gasification technology, accounts for about 5% of China's total coal consumption.

b. Higher self-reliance in energy supply and lower risk of oil and gas supply from abroad are the major drivers of coal gasification related industries.

c. China has been pushing for coal gasification in a major way by adopting proven western-developed gasifiers to gain operational experience.

d. It is the only country in the world, where large-scale coal gasification related industries play a significant role in economic development.

e. China started importing the western Coal gasification technology in 1950. Coal gasification technology was of major importance to China as it moved to prioritize, develop and use its energy resources.

f. Western gasifiers have a strong presence in China. Air Products, Siemens, KBR, GTI, Air Liquide are prominent western gasifiers in China.

g. Role of Coal Gasification in Ammonia/Urea: NH3 capacity is approx. 70 MTPA (~30% of the world) and urea capacity is approx. 80 MTPA (~40% of the world).

h. Role of Coal Gasification in Methanol: China has become by far the largest producing country in the world, representing 54% of world methanol capacity (~80 MTPA) and 48% of world methanol production in 2018.

i. China is the incremental methanol supplier to the world. Around 70% of China methanol is produced from coal.

j. Role of Coal Gasification in Ethylene Glycol (EG): Capacity of coal-based EG is approx. 2.5 MTPA (~30% of China total).

k. Role of Coal Gasification in Methanol to Olefin (MTO): Capacity of coal-based Olefin is approx. 13mt/a (~25% of China's total).

6.2 UNITED STATES

Coal gasification projects started in the 1990's in the US, however, it did not have a very successful experience. Efforts to gasify coal for power generation have failed, technologically and financially. Only two of the 25 coal-gasification electricity generating plants proposed in the U.S. since 2000 have ever come online: Southern Company's Kemper plant in Mississippi and Duke Energy's Edwardsport plant in Indiana.

Under pressure from the Mississippi Public Service Commission for having logged billions of dollars in cost overruns at Kemper and one of the reasons being the technological problems with the gasifier, the Southern company affiliate, Mississippi Power which started operations in 2014 had announced in 2017 that it will halt burning the coal at its facility, leaving Edwardsport as the only plant gasifying coal.

Edward sport, which started operations in 2013, has been plagued by technological problems and is still not running properly. Because of its operational problems and huge construction cost overruns, Edwardsport's electricity is wildly expensive. Most importantly, the natural gas prices in the US crashed post the shale oil and gas revolution which meant that the cost of producing electricity using natural gas was lower than that for coal. With abundant oil and gas reserves, sufficient production of oil and gas and declining cost of renewables – solar and wind, US is unlikely to gasify coal for power generation or for producing chemicals in the future since natural gas provides a much cheaper and technologically established option for the same.

6.3 INDONESIA

In 2022, Indonesian President Joko Widodo initiated the construction of a $2.3 billion coal gasification plant to reduce the country's liquefied petroleum gas (LPG) imports and optimize its coal resources.

The plant is designed to use 6 million tonnes (Mt) of low-rank coal to produce 1.4 tonnes of dimethyl ether (DME) annually, reducing Indonesia's LPG import by 1 Mt per year, according to state coal miner Bukit Asam (PTBA).

6.4 JAPAN

Japan has done quite a lot of research on coal gasification, especially IGCC technology and is continuing its R&D efforts in the clean coal technology space. The reliance on coal plants increased more after the Fukushima disaster in 2011. Many Japanese corporations such as Mitsubishi, Nakoso and others have developed IGCC technologies because of which Japan supports clean coal technology. According to the Ministry of Economy, Industry and Trade (MEITY), Japan will retire the inefficient older coal plants by 2030 but will continue to use Ultra-supercritical and IGCC plants. There have been two IGCC plants in operation with a total capacity of 800 MW. And another plant is likely to be added with a capacity of 543 MW this year. Therefore, Japanese have not shunned the coal gasification projects like the US, they are gradually moving ahead with this technology.

Methods for UCG operation

Generally two types of standard method for preparing a coal seam for in-situ gasification have been used successfully, namely shaft and shaftless methods. The adoptability of UCG methods is dependent on parameters such as natural permeability of the coal seam, geochemistry of the coal, seam thickness, depth, width and inclination, proximity of urban development and amount of mining desired (Wiatowski et al., 2012). The UCG process involves four steps: drilling, linking, ignition and gasification Methods for UCG operation Generally two types of standard method for preparing a coal seam for in-situ gasification have been used successfully, namely shaft and shaftless methods. The adoptability of UCG methods is dependent on parameters such as natural permeability of the coal seam, geochemistry of the coal, seam thickness, depth, width and inclination, proximity of urban development and amount of mining desired (Wiatowski et al., 2012). The UCG process involves four steps: drilling, linking, ignition and gasification Methods for UCG operation Generally two types of standard method for preparing a coal seam for in-situ gasification have been used successfully, namely shaft and shaftless methods. The adoptability of UCG methods is dependent on parameters such as natural permeability of the coal seam, geochemistry of the coal, seam thickness, depth, width and inclination, proximity of urban development and amount of mining desired (Wiatowski et al., 2012). The UCG process involves four steps: drilling, linking, ignition and gasification Methods for UCG operation Generally two types of standard method for preparing a coal seam for in-situ gasification have been used successfully, namely shaft and shaftless methods. The adoptability of UCG methods is dependent on parameters such as natural permeability of the coal seam, geochemistry of the coal, seam thickness, depth, width and inclination, proximity of urban development and amount of mining desired (Wiatowski et al., 2012). The UCG process involves four steps: drilling, linking, ignition and gasification Methods for UCG operation Generally two types of standard method for preparing a coal seam for in-situ gasification have been used successfully, namely shaft and shaftless methods. The adoptability of UCG methods is dependent on parameters such as natural permeability of the coal seam, geochemistry of the coal, seam thickness, depth, width and inclination, proximity of urban development and amount of mining desired (Wiatowski et al., 2012). The UCG process involves four steps: drilling, linking, ignition and gasification UCG techniques for different geo-mining conditions UCG techniques for different geo-mining conditions UCG techniques for different geo-mining conditions Generally two types of standard method for preparing a coal seam for in-situ gasification have been used successfully, namely shaft and shaftless methods. The adoptability of UCG methods is dependent on parameters such as natural permeability of the coal seam, geochemistry of the coal, seam thickness, depth, width and inclination, proximity of urban development and amount of mining desired (Wiatowski et al., 2012). The UCG process involves four steps: drilling, linking, ignition and gasification Methods for UCG operation Generally two types of standard method for preparing a coal seam for in-situ gasification have been used successfully, namely shaft and shaftless methods. The adoptability of UCG methods is dependent on parameters such as natural permeability of the coal seam, geochemistry of the coal, seam thickness, depth, width and inclination, proximity of urban development and amount of mining desired (Wiatowski et al., 2012). The UCG process involves four steps: drilling, linking, ignition and gasification

7. Methods for UCG operation

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7.1 Shaft method

Shaft method uses coal mine galleries and shafts to transport gasification reagents and products. Sometime it becomes necessary to make a shaft and drill large-diameter openings through underground (Wiatowski et al., 2012). Currently, the shaft method is only employed in closed coalmines due to economic and safety reasons (Wiatowski et al., 2012). Shaft method has been shown in Figure. There are four common UCG shaft methods, namely

1. **Chamber or warehouse method**
2. **Borehole producer method**
3. **Stream method**
4. **Long and Large tunnel gasification method**

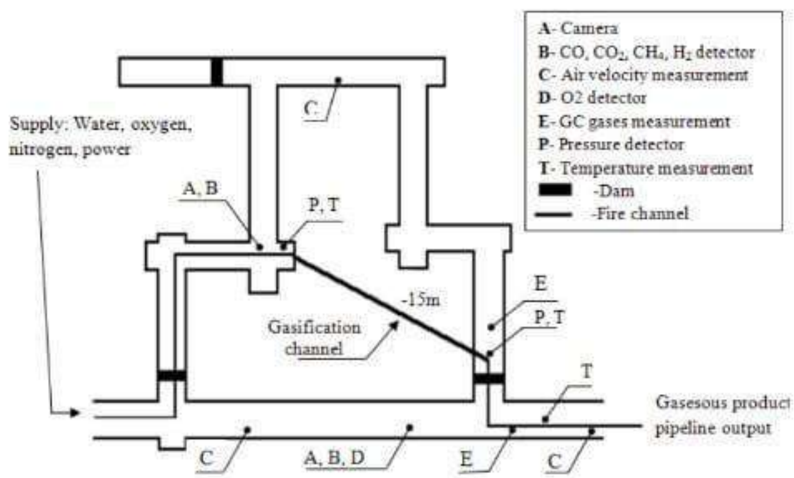

Fig. 3 Process of Shaft method

7.1.1 Chamber or Warehouse Method

This method utilises constructed underground galleries with brick walls separating coal panels. Gasification agents are supplied to a previously ignited coal face on one side of the wall and the syngas is removed from a gallery on the other side. This method strongly relies on the natural permeability of the coal seam to allow for sufficient oxidant flow through the system. The syngas composition may vary during operation and the gas production rates are often low. To improve system output, coal seams are often outfitted with explosives for rubblisation prior to the reaction zone .The process of chamber method has been illustrated in Figure

7.1.2 Borehole Producer Method

For this method, parallel underground galleries are created within a coal seam with sufficient distance between them. Galleries are connected by drilling boreholes from one gallery to other. Coal in each borehole is remotely ignited using electric current to initiate the gasification process. This method is designed to gasification considerably flat-lying seams. Some variations exist where linking of the galleries is accomplished through hydraulic and electric linking.

7.1.3 Stream Method

This method is designed for sharply inclined coal beds. Parallel pitched galleries following the contour of coal seam are constructed and are connected at the bottom of the seam by a horizontal gallery also known as a fire-drift. To initiate gasification, fire is introduced within the horizontal gallery. The hot coal face moves up the seam slope with oxidant fed through one inclined gallery and syngas leaving through the other. The main advantage of this method is that ash and roof material drop down to fill the void created during the process, which prevents suffocating the gasification process at the coal front.

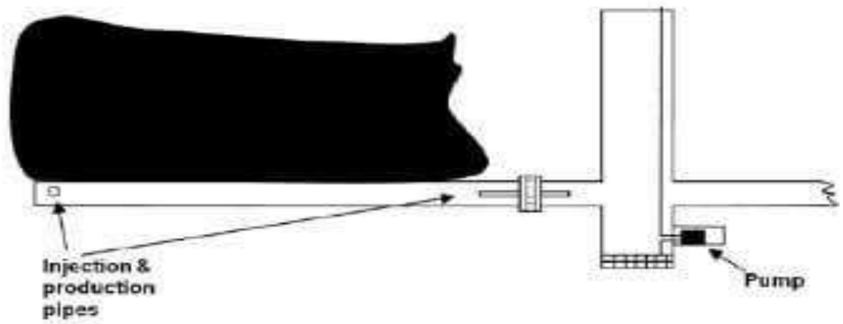

Fig. 4 Overview of stream process

7.1.4 Long and Large tunnel gasification method

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This method utilises mined tunnels or constructed roadways to connect the injection well to the production well. Typical LLT system has been presented in Fig. which consists of a gasification channel, two auxiliary holes and two auxiliary tunnels. The auxiliary holes are arranged between the injection and production wells. These are used as malfunction holes for the injection of air and water vapour, or to discharge gas for added gasifier control. The LLT also includes an auxiliary tunnel constructed with bricks, which is an auxiliary installation for air injection that prevents blockage in the gasification channel. The mined tunnels are isolated by sealing walls to prevent leakage of combustible gases from the gasifier. Location and height of oxidant injection points and gas outlet points can be adjusted allowing for two-dimensional control of oxidant injection and gas production.

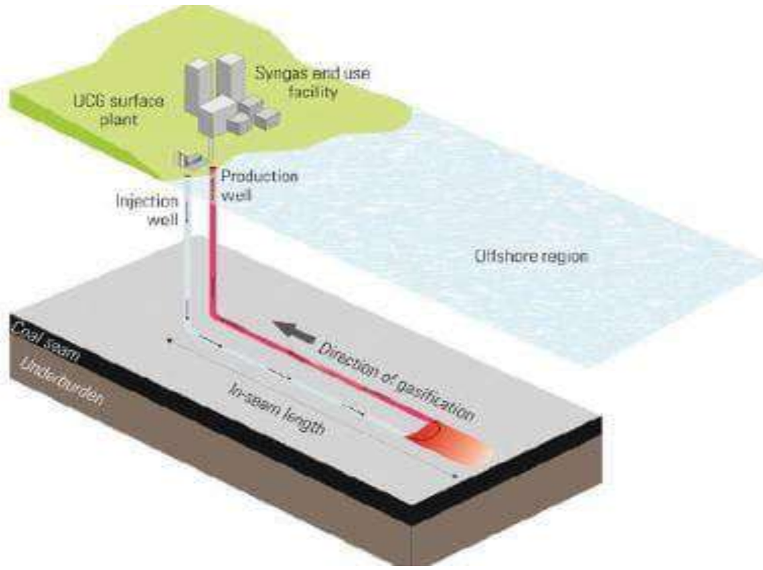


Fig. 5 Overview of Long and Large tunnel gasification method

7.2 Shaftless method

In recent times, most of the focus of research has been on the shaftless methods which employ directional drilling techniques (Hammond, 2000). With shaftless methods, all preparation and operational processes are carried out through a series of boreholes drilled from the surface into a coal seam. Preparation of a reactor for the directional drilling technique consists of creation of dedicated in seam boreholes for oxidant injection and product collection using drilling and completion technology that has been adapted for oil and gas production. The approach generally includes drilling inlet and outlet boreholes into a coal seam, increasing coal permeability between the inlet and outlet boreholes, igniting the coal seam, introducing an oxidant for gasification, and extraction of product gases from the outlet well .There are four methods of shaftless UCG, namely linked vertical well (LVW), controlled retractable injection point (CRIP), single well integrated flow tubing (SWIFT) and steeply dipping seams (SDS). However, LVW and CRIP methods are generally used in UCG due to their added advantages.

7.2.1 Linked vertical well method

LVW method is one of the oldest methods for UCG. The method was derived from technology developed in the former Soviet Union (Shafirovich and Varma, 2009). Vertical wells are drilled into a coal seam, and internal pathways in the coal are utilised to direct the oxidant and product gas flow from the inlet to outlet borehole. Internal pathways can be naturally occurring or constructed (Liang et al., 1999; Self et al., 2012). Inlet and outlet boreholes are separated by typically 500 m and linked by one co-incident horizontal well. Well 1 and well 2 are defined as oxidant supply and syngas producer respectively. Control of reactivity cavity is in reactor by oxidant rate. In its simplest form, LVW method has inlet and outlet borehole locations that are static for the life time of the system. During operation, the coal face migrates and it is found that system's control, performance, and syngas quality are affected negatively as the distance from the coal face to the oxidant injection point increases (Roddy and Younger, 2010). This factor greatly reduces the usefulness of simple LVW systems. Schematic view of LVW method has been displayed in Figure.

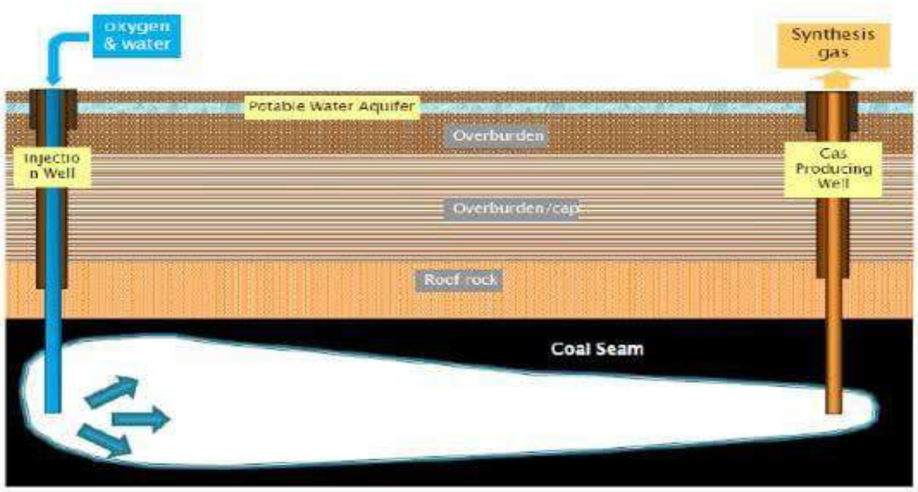
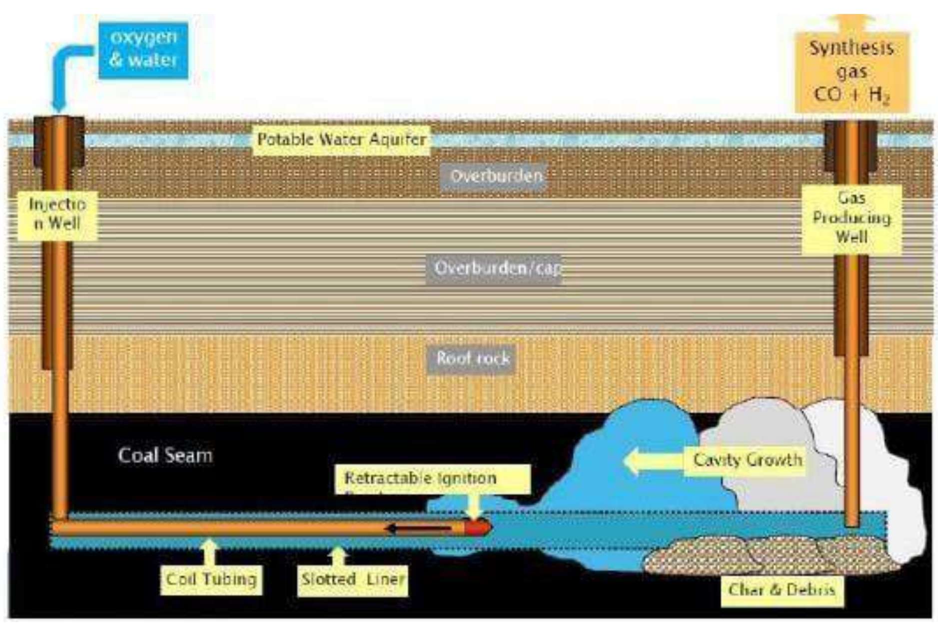


Fig. 6 schematic view of Linked vertical well method

7.2.2 Controlled Retractable Injection Point Method

CRIP method was initiated by Lawrence Livermore National Library (LLNL) during field trials in the US. It involves a movable injection point that is retracted when coal seam around the point is consumed. Gases come in contact with coal when the liner is burnt away by ignition. This method provides greater control over gasification reactor, improves resource recovery, and requires comparatively fewer wells. Two variations of CRIP technology have been practised over the years. In case of linear CRIP a number of cavities are formed in series until the eparated typically 10–30 m apart. It utilises a burner which is used to ignite the coal and positional control of oxygen injection whole coal seam is consumed. But, in parallel CRIP the cavity continuously grows along the coal. Figures show series and parallel CRIP methods respectively. A vertical section of injection well is drilled to predetermined depth, after which direction drilling is used to expand the hole and drill along the bottom of the coal seam creating a horizontal injection well. Coiled tubing is inserted into oxygen delivery well. Horizontal sections



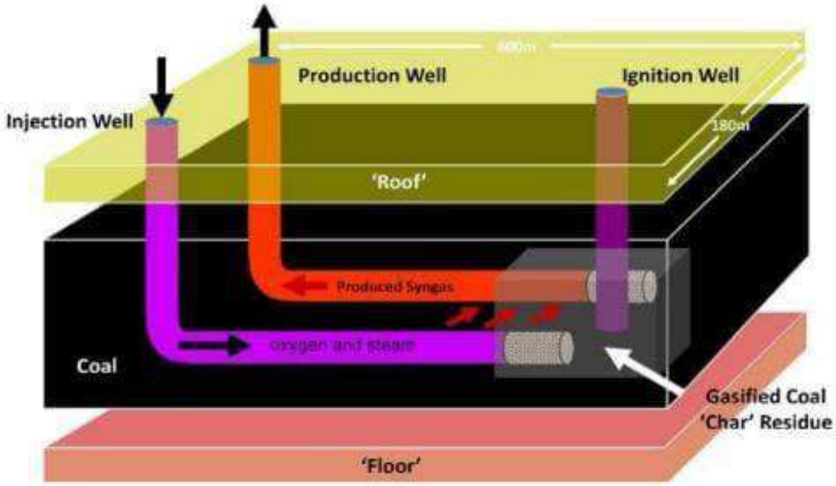


Fig. 7 Schematic view of different CRIP method

7.2.3 SWIFT METHOD

Schematic diagram of SWIFT method has been shown in Figure 13. Developer Portman Energy company used single vertical well for both syngas recovery and oxidant delivery. Single casing of tubing strings enclosed and filled with an inert gas to allow for leak monitoring, corrosion prevention and heat transfer. A series of horizontally drilled lateral oxidant delivery lines into the coal and a single or multiple syngas recovery pipelines allowed for a larger area of coal to be combusted at one time. Syngas production by SWIFT method may increase up to ten times by prior design approaches and the single well design.

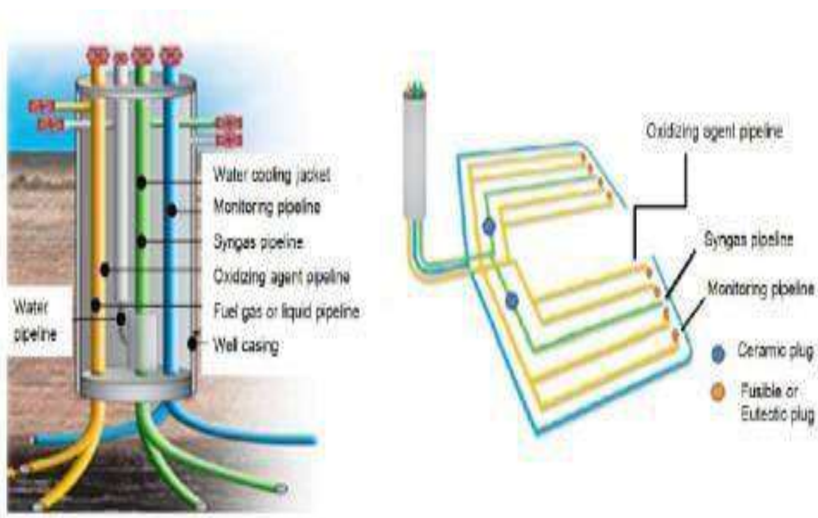


Fig. 8 Schematic diagram of Swift method

7.2.4 Steeply dipping seams

This method is applied to SDS (dip angle more than 50º) with inclined injection. In this method, injection well is drilled in lower part of the seam and production well is located at upper side of coal seam. In horizontal coal seams, inert roof material falls and remains unreacted as gases tend to move upward; while in SDS, more char is accumulated around injection well that results in improved quality of produced gas (oxidation zone remains close to injection well), whereas reduction and pyrolysis zone are extended along the path of gas (Jones and Thune, 1982). A few trials were performed on steeply dipping bed (SDB) which resulted in higher gas qualities compared to horizontal seams (Shirazi, 2012). However, this method can only be conducted in certain seams and process control is a major challenge for this method. Seam dip angle has a significant effect on UCG performance. As discussed earlier, SDS provides higher quality of syngas. However, the method creates some challenges in process control and stability. Thickness of the coal seam changes the behaviour of UCG reactor, as interaction with overburden in thin seams considerably affects UCG performance. Based on the Soviet Union UCG trials, the thickness of the coal seam should be at least 2 m to be economically feasible. UCG practice is possible in all ranks of coal; however, previous trials have shown that low-rank coals that shrink upon heating are the most suitable for use in UCG. Higher-rank coals swell after pyrolysis resulting in blockage of the link path.

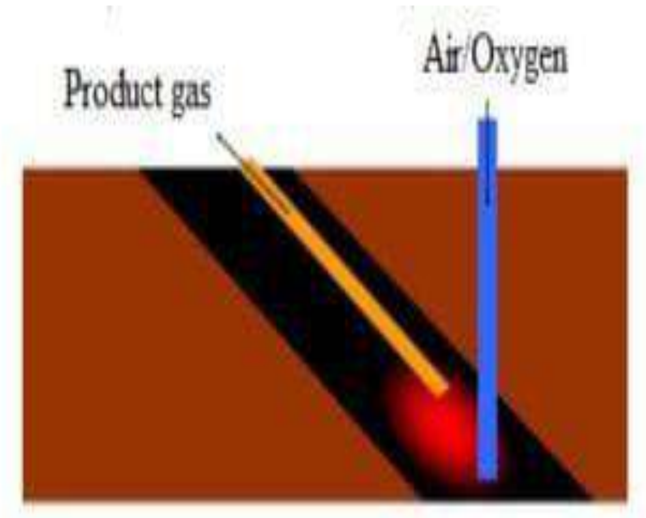


Fig. 9 SDS method

8. Advantages of Underground Coal Gasification

UCG has several advantages compared to conventional coal mining. It can be employed in areas where surface or underground mining is unable to exploit coal deposits. For example, at greater depths where surface or underground mining is unacceptable, at places where structure exploitation is not possible, and deposits that would normally be unworkable. It is also cost-effective and environmental friendly. Clean power generation through UCG-integrated gasification combined cycle (UCG-IGCC) and repowering older coal-based plants are the primary markets for underground coal gasification technology in the future. Coal-based IGCC power generation is expected to achieve a large electric market share due to its domestic abundance and relatively low and stable price. UCG-IGCC is predicted to share the ultimate and dominant market for gasification.

9. Potential Limitations and Concerns for UCG

The road to widespread commercialization still holds a number of challenges that will require research and development investment to overcome. Even though UCG has a number of advantages, the technology is not perfect, and has several limitations:

- UCG can have significant environmental consequences: aquifer contamination, and ground subsidence. While a framework can be constructed from current knowledge that can eliminate or reduce these environmental risks, as is discussed at length later in this report, it is important to proactively address this constraint on siting and operation of any future UCG projects;
- While UCG may be technically feasible for many coal resources, the number of deposits that are suitable may be much more limited because some may have geologic and hydrologic features that increase environmental risks to unacceptable levels;

- UCG operations cannot be controlled to the same extent as surface gasifiers. Many important process variables, such as the rate of water influx, the distribution of reactants in the gasification zone, and the growth rate of the cavity, can only be estimated from measurements of temperatures and product gas quality and quantity;
- The economics of UCG has major uncertainties, discussed later in this report, that are likely to persist until such times as a reasonable number of UCG-based power plants are built and operated;
- UCG is inherently an unsteady-state process, and both the flow rate and the heating value of the product gas will vary over time. Any operating plant must take this factor into consideration.

10. Description of Key Scientific Concerns

At the least, storage in evacuated cavities must occur with supercritical CO2 in order to store substantial volumes of CO2. This will limit coupled storage to UCG projects below 800m of hydrologic head, and in some cases deeper. This will also limit the timing of injection to sometime after quenching of the cavity. If not, the active or residual thermal anomalies could cause the CO2 to expand to gaseous state or at the least increase cavity pressure and attendant risk.

Unfortunately, if injection occurs after the cavity is filled with brine, any VOCs in the cavity may be forced out with the expelled water. This suggests that at a minimum hydrologic flow be confined to saline formations with good top-seals. Fortunately, the expelled water should not be buoyant and is likely to remain near the target.

Before a substantial program of intra-cavity CO2 injection begins, a number of key scientific concerns should be addressed. This initial list delineates some of the larger concerns and attempts to bound the necessary science to address them:

- **T-P constraints:** The cavity temperature at a given pressure must be sufficiently low to avoid flashing or boiling of CO2 at injection pressures. Similarly, the injection pressure must be sufficient to remain supercritical and ideally to prevent flashing. The risk of sudden phase change must be well understood as an initial condition for cavity injection, and will require both experiments and simulation;
- **Geomechanical response:** The injection pressure must exceed hydrostatic pressures in order to displace cavity water. This will prompt a number of geomechanical responses, such as fracture dilation, crustal uplift, and potentially inducing fracture. These will vary as a function of stress tensor and fracture geometry, which may be difficult to characterize in this setting. This risk may be accentuated by the collapse of the cavity roof or walls. In contrast, coal swelling will cause fracture closure. Valid geomechanical models for stress and rock deformation are required, as are coupled geomechanical / fluid-flow simulators;
- **Ground-water displacement risk:** Cavity injection above hydrostatic pressures will displace cavity brines into the coal seam and adjoining formation. This may flush VOCs or high metal concentrations from the cavity into saline aquifers or coals. The nature of these materials should be circumscribed, and the concentrations and fate of these materials reasonably well characterized through experiments and simulations;
- **Geochemical response:** CO2 injection will form carbonic acid in the cavity, which may react quickly with the coal, rock, ash, or slag in the cavity. This could leach metals into the cavity water elevating risk of groundwater contamination. Similarly, injection could mobilize sulfur from these materials to form sulfuric acid, further altering the local chemistry and increasing risk. VOCs could dissolve into the CO2 and move with mobile phases. The key suite of reactive species for typical coals should be studied experimentally as a basis for reactive transport simulation;
- **CO2 fate:** Free-phase CO2 would remain supercritical and buoyant. This would create its own upward pressure on the cavity, and lead to the same set of risks commonly considered for conventional CO2 storage. In this environment, the geomechanical, fault migration, and well-leakage risks may be greater due to the

thermal stresses and shocks of heating and quenching. The specific leakage risks for cavity storage should be further delineated and considered in concert with conventional processes (e.g., coal-gas adsorption).

The magnitude of these scientific tasks is great, and the system both non-linear and poorly constrained. As such, a substantial research effort would be required to being addressing chief concerns.

11. CASE STUDY

11.1 Ucg Trials in India

The first ever pilot project of Underground Coal Gasification was carried out in Vastan mine block, Surat, Gujarat in collaboration with Gujarat Industries Power Company Ltd. ONGC obtained the environmental clearance for the project from Ministry of Environment & Forests (MoEF), GOI, after final meeting with Expert Appraisal Committee of MoEF which was held on January 15,2010.

UCG is the only feasible technology which has the potential to convert coal resources to coal reserves. ONGC has now taken up Vastan Mine block site belonging to GIPCL in Naninaroli, Surat district, Gujarat as an R&D Pilot Project to establish UCG technology in collaboration with M/s National Mining Research Center-Skochinsky Institute of Mining (NMRC-SIM), Russia. Agreement of Collaboration (AOC) to co-operate in the Services, Operations, Development and Research related to Under Ground Coal Gasification (UCG) in India with ONGC has further been extended up to March 4, 2020. Mining lease with respect to the Vastan Pilot Project has already been awarded to GIPCL.

Moreover, a number of sites have been jointly identified by ONGC and Neyveli Lignite Corporation Limited (NLC) for studying their suitability to UCG. These are Tadkeshwar in Gujarat and Hodu-Sindhari & East Kurla in Rajasthan. One more site was jointly identified by ONGC & GMDC viz. Surkha in Bhavnagar district, Gujarat. The data of all the fields have already been analysed for evaluating the suitability of these sites for UCG. All the sites have been found suitable for UCG exploration.

11.2 Existing Coal Gasification Plants in India

(i) CO and H2 of Syn gas are important reducing agent for steel making and are environment friendly method of steel making through DRI route. Jindal Steel & Power Limited has installed world's first DRI plant based on Coal gasification technology by using domestic coal which is already operating in Angul District of Orissa for steel making. The Syn Gas project started in 2007 and commissioned in 2014. It is a technology demonstrator and can be very important for expanding the way for Sustainable and Green Development of India. With NSP of 300 Mt crude steel by 2030, the adoption of Coal Gasification technology will create a new segment of capacity addition in India, therefore minimising the need of imported coking coal.

(ii) BHEL has set up a pilot plant in Trichi and has produced 6.2 MW power but the plant has faced many issues in handling high ash coal.

(iii) M/s Thermax has also set up a pilot plant in 2014 for coal to methanol production with DST funding under the aegis of NITI Aayog in Pune.

(iv) L&T has commissioned many gasifiers in China and are in the business of erection and commissioning of gasifiers.

11.3 Ongoing Surface Coal Gasification Projects

Setting up of coal gasification plant is a capital-intensive work. Further, the experience of coal gasification in India is limited. As such the success of initial coal gasification projects is very important for the national mission. It has been planned to set up two gasification projects on pilot basis one on high ash coal blended with pet coke and the other from low ash coal for the purpose of establishing technology.

Details of these Two Projects are as Mentioned Below:

11.3.1 Talcher Fertiliser Plant

A joint Venture Company named Talcher Fertilizers Limited (TFL) comprising of RCF, CIL, GAIL and FCIL has been constituted (2016) to set up a Surface Coal Gasification based integrated fertilizer complex using high ash coal from nearby Talcher Coalfields mixed with pet coke from Talcher refinery with an Investment of Rs 13277 cr. Coal blended with pet-coke up to 25% shall be gassified to produce syngas, which shall be converted into Ammonia and subsequently to 1.27 Mt tonnes of neem coated Urea annually.

TFL Board approved coal gasification technology of M/s Air Products (earlier M/s Shell) for the proposed plant. Exclusive subsidy policy for urea produced through coal gasification route by TFL has been approved by the cabinet in 2021. This will ensure concession rate/subsidy for the urea produced through coal gasification route by TFL for a period of 8 years from the date of start of production and will be determined by providing 12% post tax IRR on equity. Hon'ble Prime Minister of India had laid the Foundation Stone of the plant at Talcher on 22.09.2018. M/s Projects & Development India Limited (PDIL) is the Project Management Consultant (PMC) for this project. The project is being implemented on partial Lump Sum Turn Key (LSTK) basis. LSTK tenders for major plants (Coal Gasification & Ammonia-Urea) are under evaluation. NIT for Captive Power Plant and other Off-sites & Utilities are under preparation by the consultant. Currently, all pre-project works such as Commissioning of Water System, Supply-cum-Erection for Power Works, Land Development etc. are progressing in full swing.

11.3.2Dankuni Coal to Methanol Plant

In pursuance to initiatives towards development of Clean Coal Technology and alternate use of coal, CIL has floated a tender for engagement of an agency on BOO basis for setting -up a coal-based Methanol plant of a 2050 MTDA (0.676) capacity in the premises of Dankuni Coal Complex (DCC) near Kolkata. Coal sourced from Raniganj coalfields shall be gassified to produce syngas which shall be subsequently converted into methanol. The project will come up with an investment of about Rs 5800 Crs and 1.5 MT Coal will be supplied from Sonepur Bazari Mines of ECL.

11.3.3 Other Proposed Projects

CIL has further identified four different coal gasification projects in ECL, SECL, WCL and CCL wherein methanol, ammonia, ammonium nitrate and urea are expected to be produced. The pre-feasibility report has been prepared by PDIL and CMPDI has been engaged as a principle implementing agency for the project getting completed. NLCIL has also taken up one lignite to methanol project at Neyveli.

11.4 Indian Strategy for the Future of Coal Gasification

Honourable Prime Minister had announced a vision of 100 MT Coal Gasification by 2030. At present most of the coal produced in India is utilised in thermal power plants for power generation. Due to environmental concerns, in all likelihood, the requirement of coal for thermal power generation will reduce in long run. Accordingly, there is a need to find an alternative use of coal to prolong the life of coal and utilize the natural resources available in the country.

12. RESULT AND CONCLUSIONS

UCG has the potential to unlock vast amounts of previously inaccessible energy in un mineable coal resources. However there are formidable obstacles to be overcome before this is possible, many of which are associated with the fact that the process takes place deep underground in a context where it is difficult (or impossible) to monitor and control the conditions. It seems probable that each potential UCG site will be unique as, in many senses, is every underground mining site. Conventional mining techniques developed over several decades and the necessary rules governing the conditions for safe extraction were heavily influenced by the results of serious accidents involving loss of life. While UCG involves entirely different risks, particularly in terms of the possibilities of water contamination, there will be no men working underground. However, the uncertainties need to be properly assessed, based on the emerging experience gained from the current projects.

UCG requires a multi-disciplinary integration of knowledge from exploration, geology, hydrogeology, drilling, and of the chemistry and thermodynamics of gasification reactions in a cavity in a coal seam. This involves rethinking almost all past experience connected with coal utilisation because there is commonly little contact and technical understanding between those who mine coal and others who use it. Even at an academic level, there are few experts who can cut across the boundaries between the geologists and mining engineers responsible for coal extraction, and the chemical and process engineers largely responsible for its use.

In addition, many coal experts have developed an in-depth knowledge and understanding of their own coals and of their geological settings, but have limited practical knowledge of the coals and their associated geology which occur in other places. Where coal is mined, geological expertise is focused on its impact on conventional mine design, construction and operation, and in many places this is based on decades of experience. The behaviour of an UCG reactor/cavity is quite different and there is as yet very limited experience of what happens. UCG has the potential to provide access to vast coal resources and unlock a significant new source of energy for the future. While there are challenges to overcome, the benefits of UCG make it a promising technology for the energy and chemical industries. With careful planning and management, UCG can be carried out safely and sustainably, providing a pathway to a cleaner energy future.

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