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Underground Coal Gasification: an alternate, Economical, and Viable Solution for future Sustainability

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ABSTRACT: *The Energy demand in the world is increasing drastically, and coal is the major raw material in producing energy. Countries such as China, USA, India, Australia, Indonesia, Russia, South Africa, Germany, Poland, and Kazakhstan play a vital role in hard coal strip surface mining: extracting of coal through Mining process is dangerous work, as most of the coal is too deep, and creates unwanted pollution and is economically not effective. Coal releases enormous quantity of unwanted green house gas emission when it is burnt. Therefore, there is a need in technology for clean and efficient usage of coal: Underground coal gasification (UCG) is an economical, clean coal technology using un-mined method of converting coal into a combustible gas in-situ, without bringing up the* CO_2*, and ash residue which is left out after burning the coal. This process is performed under the earth surface in-order to eliminate traditional method of extracting the coal through strip coal mining process. UCG offers more proven advantages over conventional Mining and gasification. This is an attempt to show that UCG is an alternate, economical, and viable solution for future sustainability.*

KEYWORDS: *Underground coal gasification (UCG), Gasification, Coal, Combustion, Mining, Hydro-Fraccing, Drilling, Inseam channel construction; Linked Vertical wells, Controlled retraction injection point (CRIP, single Well Flow Tubing, Zones, Carbon capture and storage of carbon dioxide, Syngas.*

I. INTRODUCTION

The consumption of Energy is drastically increasing day by day with the rapid increase in the world's population and with the quick development and quest for intuitiveness in the daily use equipments. Most of the equipments we use today; consumes electricity, and most of the electricity is generated from fossil fuels [*1*]; which increases the level of global warming due to the unwanted green house gases (GHG) emission spread in the atmosphere. With these unwanted gas emissions there is a direct effect on the environment such as increase in the sea level, contamination of surface as well as underground water, risk to aquatic animals, acid rains, hurricanes, floods, tornadoes, spread of diseases and drought in the tropical area which are nearer to the equator [*2*],[*3*]. As coal is becoming a scarce resource, it is not only the second most significantly used fuel but also the main source of huge damage to the environment [*4*]. In contrary UCG is one of the un-mined means of generating electricity by low carbon, minimal green house gas emission, avoids environmental effects, safety risks, and health risks [*5*],[*6*].

Fig. 1 illustrates the working of the UCG technology. In UCG process two or more wells are drilled under the ground until the coal seam to inject the mixture of oxidants (Steam or air/oxygen) for gasification, and the resulted gas is called synthesis gas (Syngas) [*7*]. The product gas drawn from surface is collected through the production well. The coal seam is ignited via the injection well and it is burned at a temperature over 1,500° K (1,230° C). During combustion process, CO (carbon monoxide), CO_2 (carbon dioxide), H_2 (hydrogen), H_2S (hydrogen sulphide), and CH_4 (methane) is produced at high pressure [*6*]; the ash residue is left in the ground [*8*]. The rate of the gasification is controlled with the airflow pressure and temperature by the operator. UCG process on coal seam is performed deep below the water tables, because the over lying weight of the water needs more pressure for gasification to be pumped by an UCG operator up on the surface [*8*]. The extracted Syngas is cleaned and used for generating power, Industrial heating, liquid fuel production, and in chemical manufacture for feedstock [*7*]. The area of the burnt coal are immediately depleted, the age, natural history, and composition which are the main factor which decides the coal, and its resistance to flow. The coals natural permeability is not satisfactory to transport the gas. During high pressure breakup of coal reversible combustion, hydro-fraccing, and an electrical linkage are used for varying the degrees [*6*].

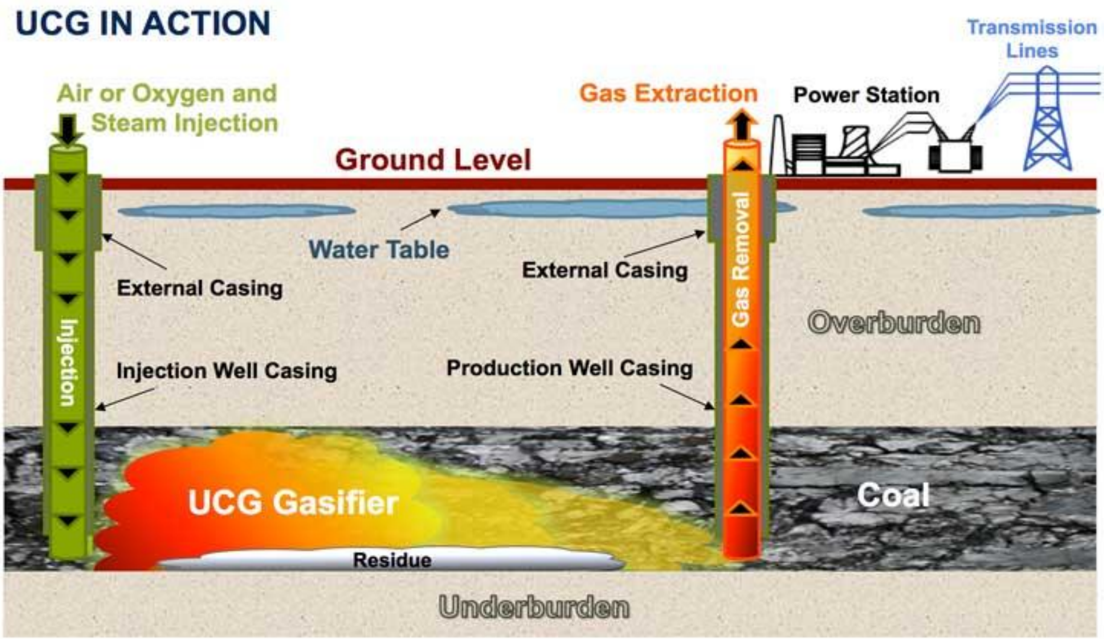


Fig. 1. Underground gasification of coal [*9*]

II. PROBLEM-HARD COAL STRIP SURFACE MINING

The economical and environmental friendly method of UCG has been successfully running in different parts of the world [*10*], comparatively the usage of traditional method of coal extraction from the earth is significantly more. By surface coal mining (traditional method) over 6185 million tons (Mt) of coal is produced worldwide and 1042 Mt of brown coal ignites. Table 1 shows the top ten hard coal producers. Most of the coal extracted is used by the country itself; around 15% of hard coal production is destined to international coal market [*11*].

Table 1: Top Ten Hard Producers (2011e) [*11*]

Country	**Quantity**
PR China	3471Mt
USA	1004 Mt
India	585 Mt
Australia	414 Mt
Indonesia	376 Mt
Russia	334 Mt
South Africa	253 Mt
Germany	189 Mt
Poland	130 Mt
Kazakhstan	117 Mt

III. HISTORY AND BACKGROUND OF UCG TECHNOLOGY

In early 1868 two German brother engineers' Werner, and Wilhelm Siemens recommended UCG. A Russian scientist named Dmitry l. Mendeleev independently developed a detailed design invention of UCG operational concept, and published throughout 1880's and 90's in his body of work. In 1909 an American inventor, A.G.Betts received patent for his work towards UCG.

In 1912 an English chemist, Sir Williams Ramsey announced an experiment plan on UCG. Unfortunately the experiment did not succeed due to his death. Later because of the onset of World War l, the entire UCG experiments were stopped and were not started for 30 years until World War ll.

UCG trial by Ramsey has been successfully finished. In May 1913 Vladimir Lenin published in Pravada article stating UCG as "One of the great triumphs of technology" [*12*] and admiring it as a social significance because of the hard core mining labor elimination. In USSR the development of the UCG was stopped for 70 years because of wrong assumption.

In 1928 UCG program was launched, and was personally supervised by Joseph Stalinn at the former Soviet Union; the development led them to extract commercial quantity of coal. In 1937 the first commercial UCG plant was established. In 1996 the Russian UCG plant was shut down, till then Soviet Union had extracted more than 17 million tons of coal. In 1960's large reserves of natural gas and coal was discovered in Russia, and by then the Soviet Union UCG program was significantly downsized

An alternate and dissimilar UCG activities approach in Western Europe (Belgium, Germany, France, Spain, Great Britain, and others) has not resulted in any development of UCG process to be implemented in coal recovery on a commercial scale.

In USA, advancement of UCG was started in early 1970's to mid 1980's. In 1998, 30 UCG experiments were conducted during culminating in Rocky Mountains 1 by the US department of energy. The rise of fuel prices, decreased gases, and to be reasonable, the government abandoned the program before it had a chance to implement a commercial based UCG technology [*13*] [*14*]

After conducting series of trials, recently the advancement in directional drilling, and due to increase in the consumption of energy worldwide, focus of more environment friendly generation of energy has finally led to UCG invention. The historical design evolution of UCG includes Controlled Retracting Injection Point (CRIP), Linked Vertical Well, Steeply Dipping Bed, and Tunnel. The Commonwealth Scientific Industrial research Organization, Australia's leading research organization was developing and researching for the following 10 years for Carbon energy proprietary UCG technologies key seam®, and it was born out to identify the hurdles to commercialize UCG technology in over 60 projects around the world [*15*].

In 1993, when the UCG technology was declining and neglected, Ergo Exergy Technologies Inc started a UCG plant at Montreal, Canada. At the end of 1999, with continuous trials in six years they produced their first UCG Syngas project in Chinchilla, Australia. Dr Len Walkem, an Australian Business man took a decisive role to establish UCG project. In recent days the Ergo Exergy is now participating in commercializing UCG, which are currently running at various stages of development throughout the world; Australia, Europe, Pakistan, New Zealand, South Africa, USA, and India. The power generation target of these projects is to generate in Integrated gasification combined cycle (IGCC) and co-firing configuring, and replacement of the natural gases for power plants and production of synthesis liquid fuels, synthesis methane, and fertilizer [*13*]

There are three methods of UCG technology of which two are commercially available in the market whereas the third method has been recently announced [*16*].

IV. CHANNEL CONSTRUCTION

The UCG process is very simple and attractive but the concept of converting the process in to large scale has proved more difficult from the previous reverse combustion. During long distance gasification, before igniting and gasification, cavity is developed in the coal seam. Good drilling technique is necessary to construct and connect vertical and horizontal wells, as shown in the Fig. 2 and 3 [*17*].

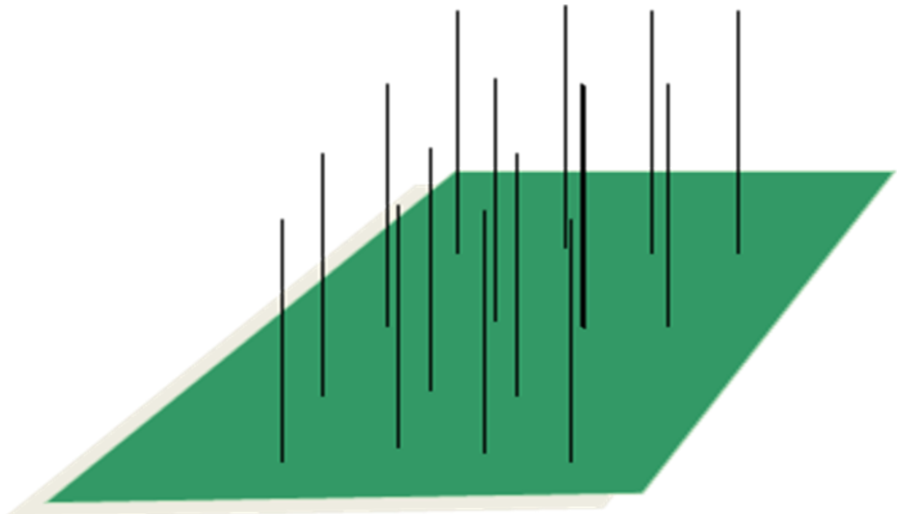


Fig. 2. Vertical wells

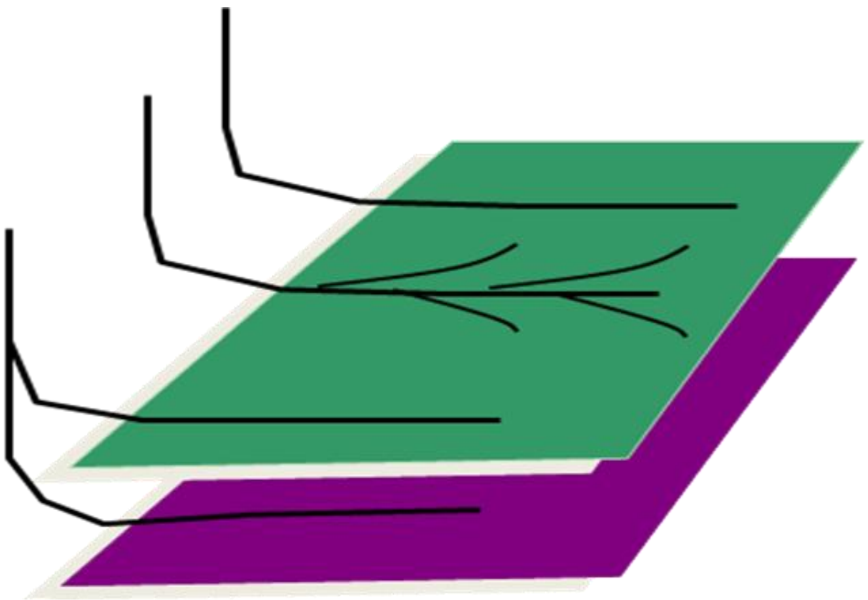


Fig. 3. Horizontal multilateral wells

Various approaches has been attempted to construct in seam channel [*18*]**.**

1) Drilling from an outcrop
2) Slant drilling from the surface
3) Constructing man-made in-seam galleries
4) Directional drilling

The above methods are the various trials and commercial project that took place. But from the recent survey no consensus notifies that the constructed well is reliable and economical process. In 1990's the advancement of the directional underground drilling process had resulted in developments in oil and gas industries. Similar method is used for regular degasification of coal seam in Australia, South Africa, and United States. For the first time, the construction of in-seam coal wells was dependable and precise, with minimal failure of risks than previous encounter. The deeper drilling of coal seam: 1000 m has further made advantage for CO2 sequestration, cavity growth, power output and environmental benefits.

V. WELL CONSTRUCTION AND LINKAGE

Wells are constructed under the earth surface in to the coal seam. The construction of the well varies and it depends on whether it is used as injection well or production well.

The injection and production wells should be linked and it is necessary to make sure that there is a flow path between the wells. The linkage of wells will assist the cavity development and compilation of product gas. Different ways of linkage methods are discussed below [*19*]:

1.1. In-seam directional drilling

In this method a horizontal drill is developed in the coal seam between the two wells.

1.2. Artificial fracturing

This method involves cracking of coal by pressurizing it by either using water or air between the wells.

1.3. Reverse combustion

This method involves igniting the coal seam and forming a channel link between the wells by combusting. The direction of flow is reversed and gasification commences.

VI. DEPTH AND THICKNESS OF VARIOUS FIELD TRIALS

The major countries around the world which have adapted UCG technology instead of traditional way of extracting coal are: Australia, New-Zealand, Eastern Europe, USSR, Western Europe, Africa, Europe, USA, and China. The depth and thickness of the UCG process till 2005 are as shown in the Fig. 4 [*20*]

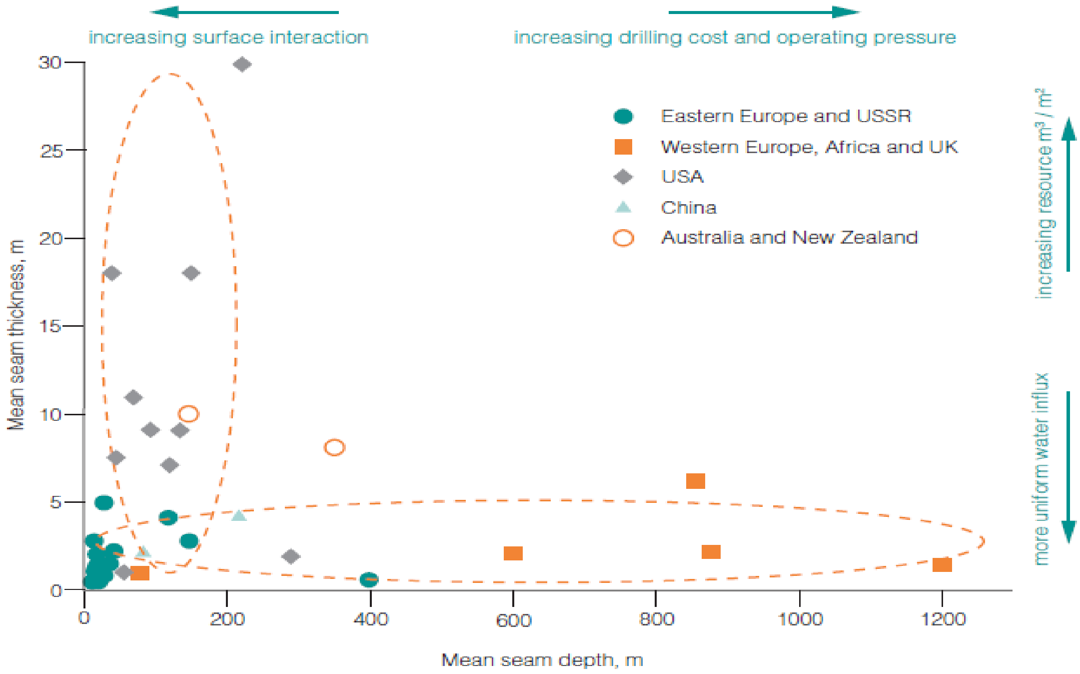


Fig. 4. Thickness and depth of the coal seams of various field trials of UCG till 2005

VII. UCG PROCESS INVOLVEMENT IN UNDERGROUND LEVELS

The different layers and UCG process are as shown in the Fig. 5 [*21*]. The UCG process undertakes in coal seam which is after 4 layers. The advantage of UCG process is, it does not have any effect the above 4 layers which includes Ground Level, Soil & Rock, Fresh Water Aquifer, and Impermeable Overburden.

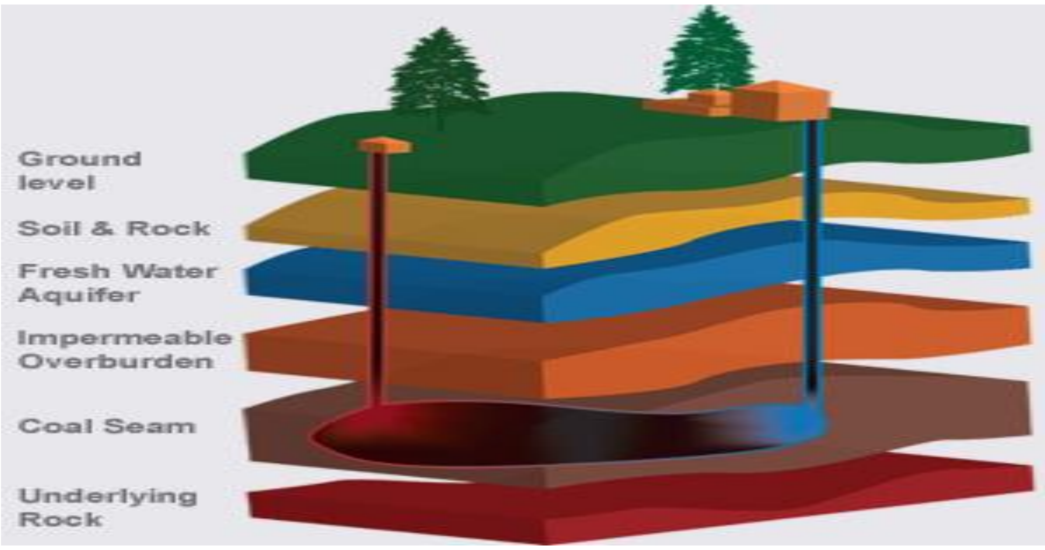


Fig. 5. UCG process and different underground layers

VIII. GASIFICATION

Gasification is a chemical process in which solid/liquid fuel phase changes in to combustible gas, which is later used to test the general permeability of coal seam gases and it is proved that passing from the combustion zone is un-reliable. The flow path of combustion gases can be improved by Hydro-fraccing. The waste products generated in the gasification process should be controlled to avoid environment contamination. The underground gasifier is built beneath the ground as hydrocarbon reserves by injecting air or oxygen to coal. Therefore, it undergoes a combustion process/gasification process as shown in the Fig. 6. The product gases are drawn to the surface for processing, and finally utilize to generate Power or Chemical bi-products: hydrogen, methanol/ synthesis natural gas.

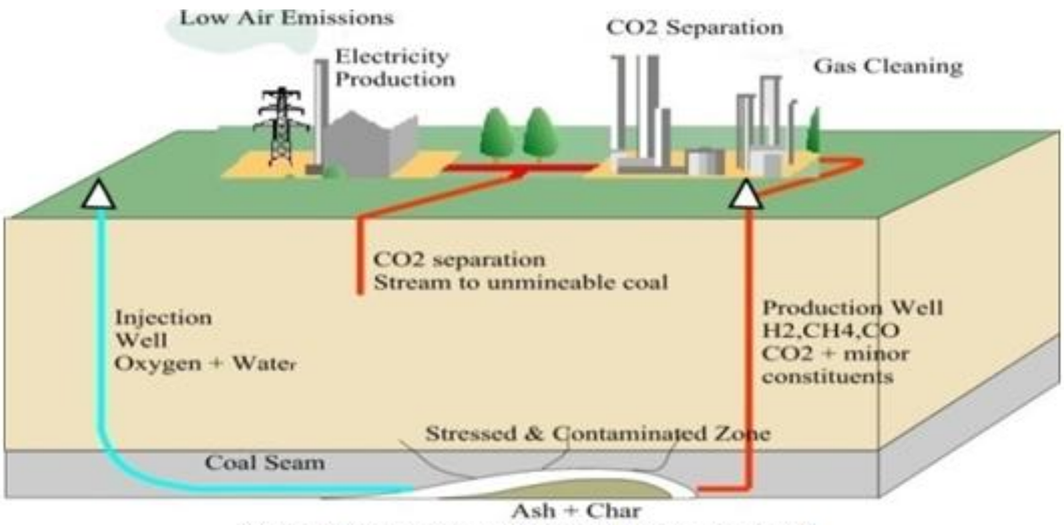


Fig. 6. Underground gasification of coal process [*18*]

IX. DIFFERENT METHODS OF UCG TECHNIQUES

2.1. Vertical wells with a reverse combustion

A linked Vertical well with reverse combustion process is shown in the Fig. 7 [*22*].

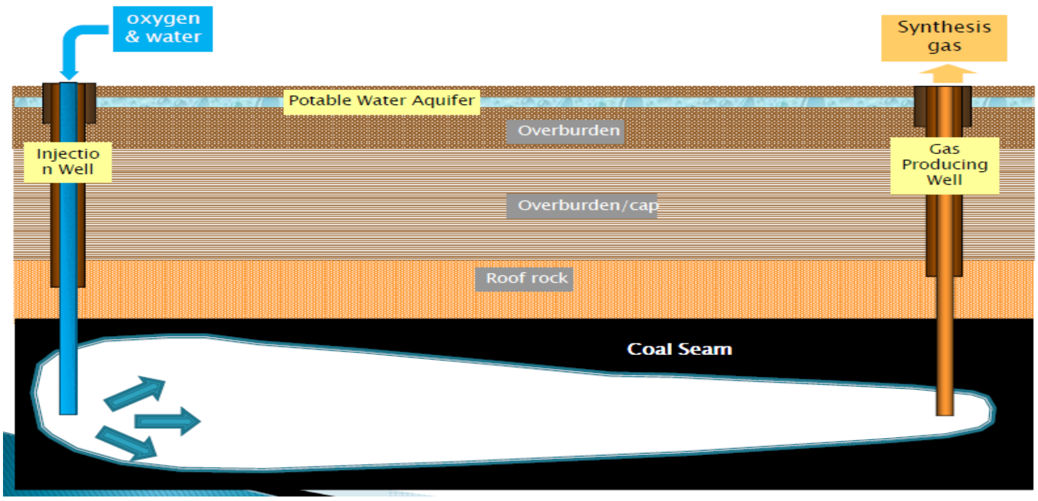


Fig. 7. Vertical wells with a reverse combustion to open the internal pathways in the coal

The first method is vertical wells with a reverse combustion to open the internal pathways in the coal. This method uses air and water as injected gases, and was used in Soviet Union [*6*], later it was tested in chinchilla, Australia (1999-2003). In Russia the pre work was focused on the exploitation of shallow and often it was the thin coal seams that were easy to drill but they were not economically or environment friendly and suitable today. The shallow seams were comparatively low quality gas and low pressure in the reactor with deeper systems. Moreover there were difficulties in forming a physical connection between the vertical wells, which resulted in high failures of early UCG work. Due to high gas loss, there is a potential breakthrough to the surface because fracturing, possible contamination of ground water, and the shallow seams were un-suitable. Unless or until there is a multi-seam environment the thin seams which are less than 2 meters are hard to use [*16*].

2.2. Controlled retraction injection point (CRIP)

Controlled retraction injection point (CRIP) as shown in the Fig. 8 [*16*]; was tested in Europe and American coal seams. By drilling and completion technology it forms in seam boreholes, and modified to extract oil and gas. This method uses oxygen or air for gasification using a movable injection point which is known as CRIP. At first seem drilling was identified as an option, but later steerable drilling was available in (1975-1990) which was developed by the US program of UCG, and the process was combined with CRIP [*16*].

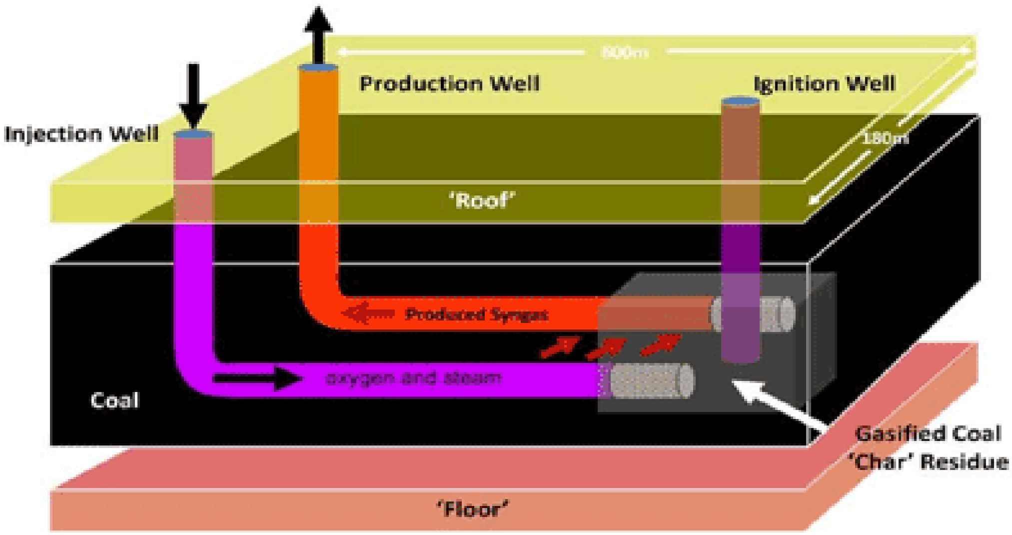


Fig. 8. Controlled retraction injection point (CRIP)

2.3. SWIFT (single Well Flow Tubing)

In May 2012, Portman Energy announced that they developed a new method of UCG, which is called Single Well Flow Tubing (SWIFT) technology. It uses a single vertical well for both injecting oxidants and delivery of Syngas as shown in Fig. 9 [*22*]. The unique design of this method is, it uses a single casing tube string which is enclosed and filled with inert gas for corrosion prevention, leak monitoring, and heat transfer. This method consists of series of horizontally drilled holes; later oxidant exit lines in to the coal seam, and a multiple or single Syngas recovery pipelines will allow the coal for larger area combustion at single time. The developer claims that the production by using this method will have up to 10 times prior design approaches and the development cost for single well design is significantly low. The facilities and well heads are concentrated at a single point pipelines, facility footprint, and reducing surface access roads [*22*]; [*23*].

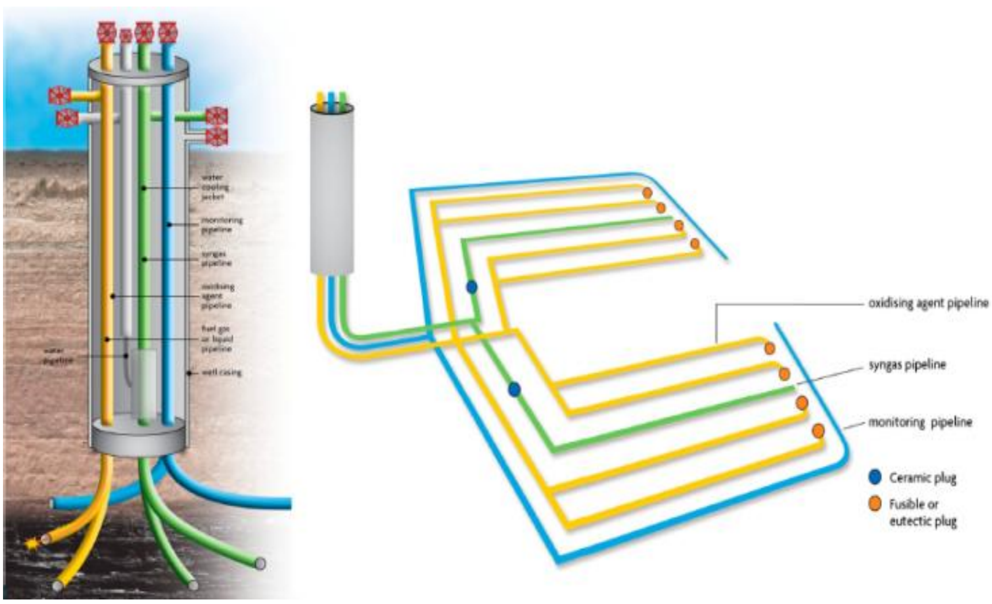


Fig. 10: SWIFT (single Well Flow Tubing)

X. ZONES AND CHEMICAL REACTION & ITS END PRODUCTS

UCG process is divided into three different zones: oxidization zone, reduction zone, and dry distillation zone as shown in the Fig. 11 [*24*], and is illudtrated below in detail [*19*].

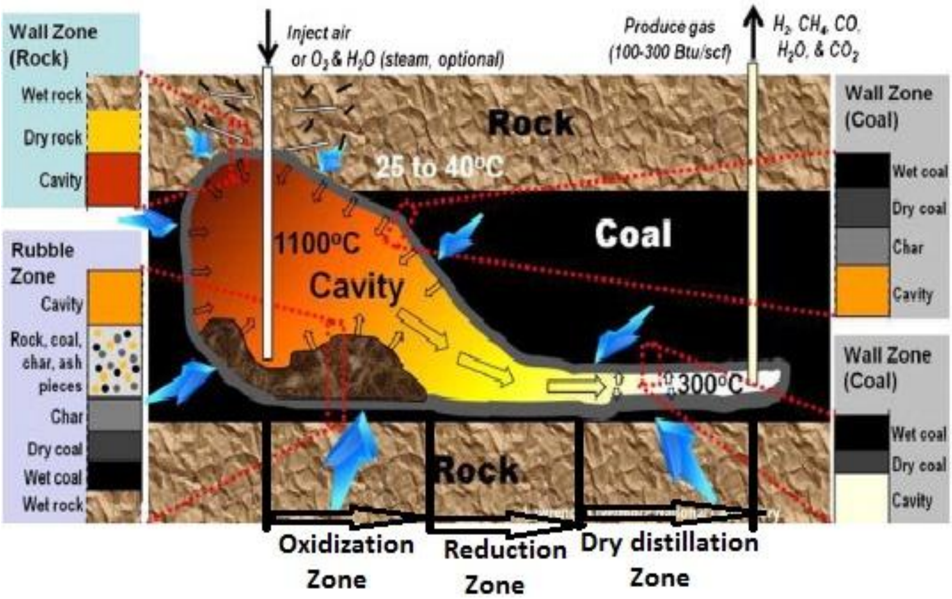


Fig. 11. Underground coal gasification zones

3.1 Combustion or oxidation zone reaction

Oxygen and coal are combusted and the process generates heat (exothermic reaction), and various other gases are further used in later reaction stages. The reactions are:

$C + O_2 = CO_2$ + heat (complete combustion)
$C + 1/2\ O_2 = CO$ + heat (partial combustion)
$CO + 1/2O_2 = CO_2$ + heat

The gasification process progressively consumes coal and creates a cavity. With time the cavity expands in the path of flow of gases towards production well. The combustion process is controlled by quenching inward flow of ground water. The rate of ground water flow is governed by several factors, but the main cause is operating pressure.

3.2. Reduction zone reaction

In this reaction the heat generated from the combustion stage is utilized in reduction zone reaction. The reactions are:

$C + H_2O$ + heat= $H_2 + CO$
$C + CO_2$ + heat = 2CO

The above reactions are heterogeneous (gas/solid reaction)

The gas undergoes only homogenous reaction till the gas reaches equilibrium composition. The water vapour present in the composition promotes water gas shift (WGS) reaction that contributes H_2/CO balance. The reactions are:

$CO + H_2O \leftrightarrow H_2 + CO_2$ (WGS reaction)
$CO + 3H_2 \leftrightarrow CH_4 + H_2O$ (Methanation reaction)

The equilibrium gas composition dictates pressure, temperature, composition of gas, and quantity of water vapour once the heterogeneous reaction is complete.

3.3. Pyrolysis

At close to 400° C, the coal loses its moisture and undergoes thermal decomposition (pyrolysis);

Coal= $CH_4 + H_2O$ + Hydrocarbons + Tars + Volatile gases

The hydrocarbons and tars depend on the temperature of whether it is consumed or entrained in the product gas

3.4. End products of UCG

The percentage of each raw material produces in UCG of coal is shown in Table 2 [*25*].

Table 2: Range of raw product gas composition from oxygen fired UCG

Component	Quantity
Hydrogen (H_2)	20-30
Carbon-monoxide (CO)	10-20
Methane(CH4)	5-12
Carbon-dioxide (CO_2)	20-40
Water (H_2O)	1-30
Tars	0.1-1
Ammonia(NH_3)	0.1-1
Hydrogen Sulphide(H_2S)	0.1-1

XI. CARBON CAPTURE AND GEOLOGICAL STORAGE OF CARBON DIOXIDE (CCGC)

The working procedure and steps carried out in CCG technology is as shown in the Fig. 11 [*24*].

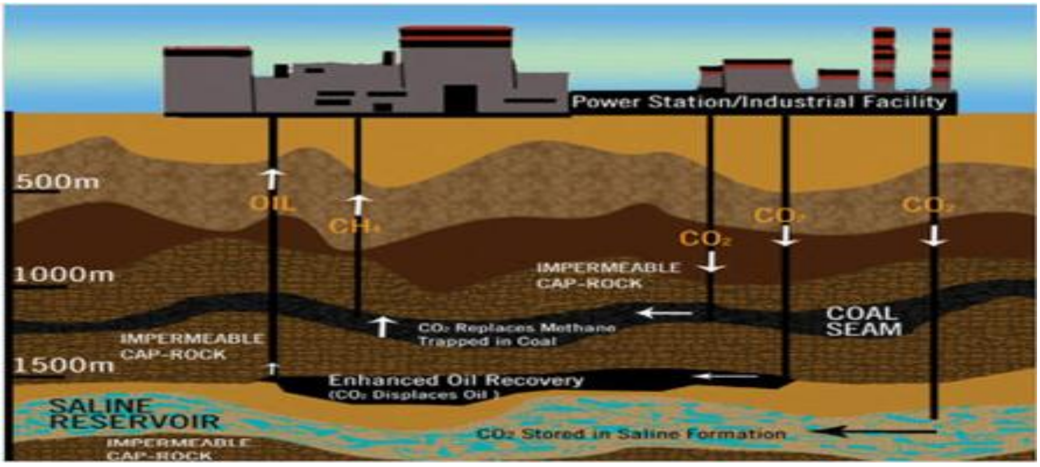


Figure 11: Carbon capture and geological storage of carbon dioxide (CCGC)

CCG is a method of controlling carbon dioxide (CO_2) emission in to the atmosphere.

4.1. Close Coupled UCG with CO_2 storage

UCG process itself lends carbon capture and sequestration option, as the process generates Syngas at a pressure, temperature and CO_2 concentration that enables low cost carbon and simple to use.

The carbon produced in the UCG process of Syngas provides an opportunity to compress, and captures it in pipelines for enhanced coal bed methane (ECBM) or enhanced oil recovery (EOR) underground storage.

4.2. Storage of CO_2 in UCG seams

Different ways of CO_2 capture process: [*16*].

4.2.1. Post-combustion

In this process the CO_2 is separated from the exhaust gases after combustion of fossil fuel. The system methodology is similar to those of already used to remove pollutants such as nitrogen oxide, sulphur oxides from many power plants. The post combustion CO_2 is not yet been commercialized for large scale CO_2 removal and is now technically available for coal based power plants.

4.2.2. Oxy-fuel combustion/Oxy-firing

In this process the combustion of coal takes place in pure oxygen instead of air to fuel convectional steam generator. The introduction of nitrogen is avoided in to the combustion chamber and the quantity of CO_2 in the power station exhaust is highly concentrated, making it easier to compress and capture. The oxy-fuel combustion with CO2 is still in demonstration phase.

4.2.3. Enhance coal bed methane

UCG in combination with CO_2 injection into adjacent coal seam to ECBM is a potentially good/attractive option, particularly for under river estuaries near-shore and eventually for offshore coal. The introduction of CO_2 in to coal seams displaces methane and itself is absorbed on to the coal in a physical bond as enduring store. ECBM tests were undertaken in Japan, china, Poland (REPOCOL), and United States with encouraging results.

With recent research in Australia, UCG tests proved a reduced cost to CBM (Coal Bed Methane), also substantial quantities of Methane can be acquired using UCG technology.
During UCG process the storage of CO_2 in and around the coal seam cavity, or close to saline acquifiers is currently underway across the world. The results so far look promising.

XII. SYNGAS

In the below shown Fig. 12 [26], Syngas feedstock is used for various purposes such as Synthetic transport fuel to create less emission travelled per kilometer with mineral fuels, fertilizers to improve the food production, waxes, detergents, pure hydrogen, and plastics [*8*]; Syngas is generally used for power generation to produce liquid fuels and to make fertilizers [*26*].

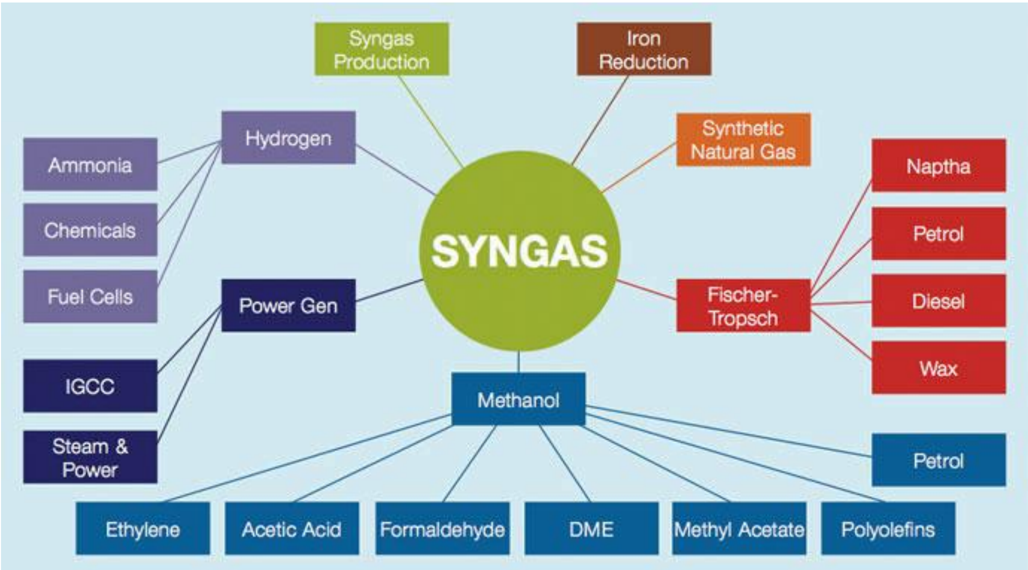


Fig. 12: Uses of Syngas in wide varieties

XIII. COST OF UCG POWER GENERATION

In the below shown Fig. 13 [*16*]., the cost of UCG power generation is cheaper compared to Renewable, Nuclear energy, Clean cola, and clean gas techniques

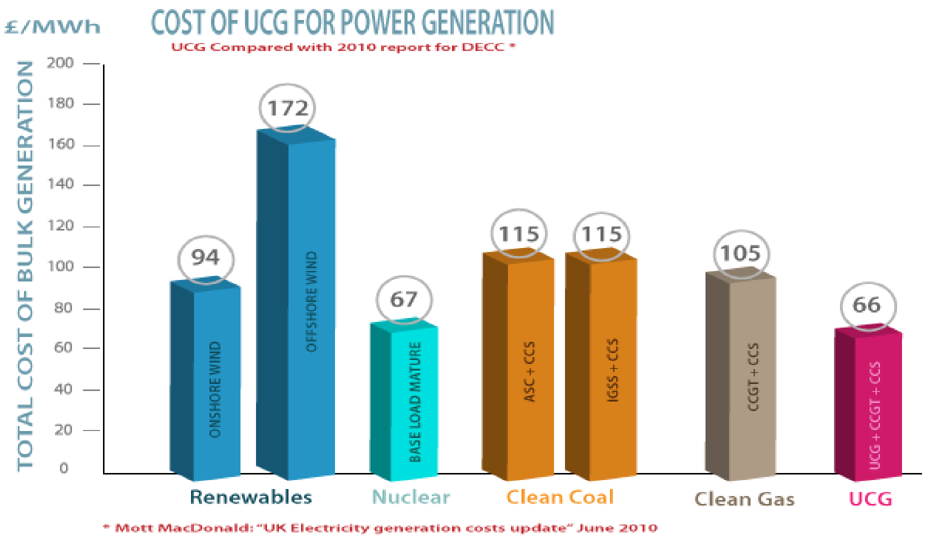
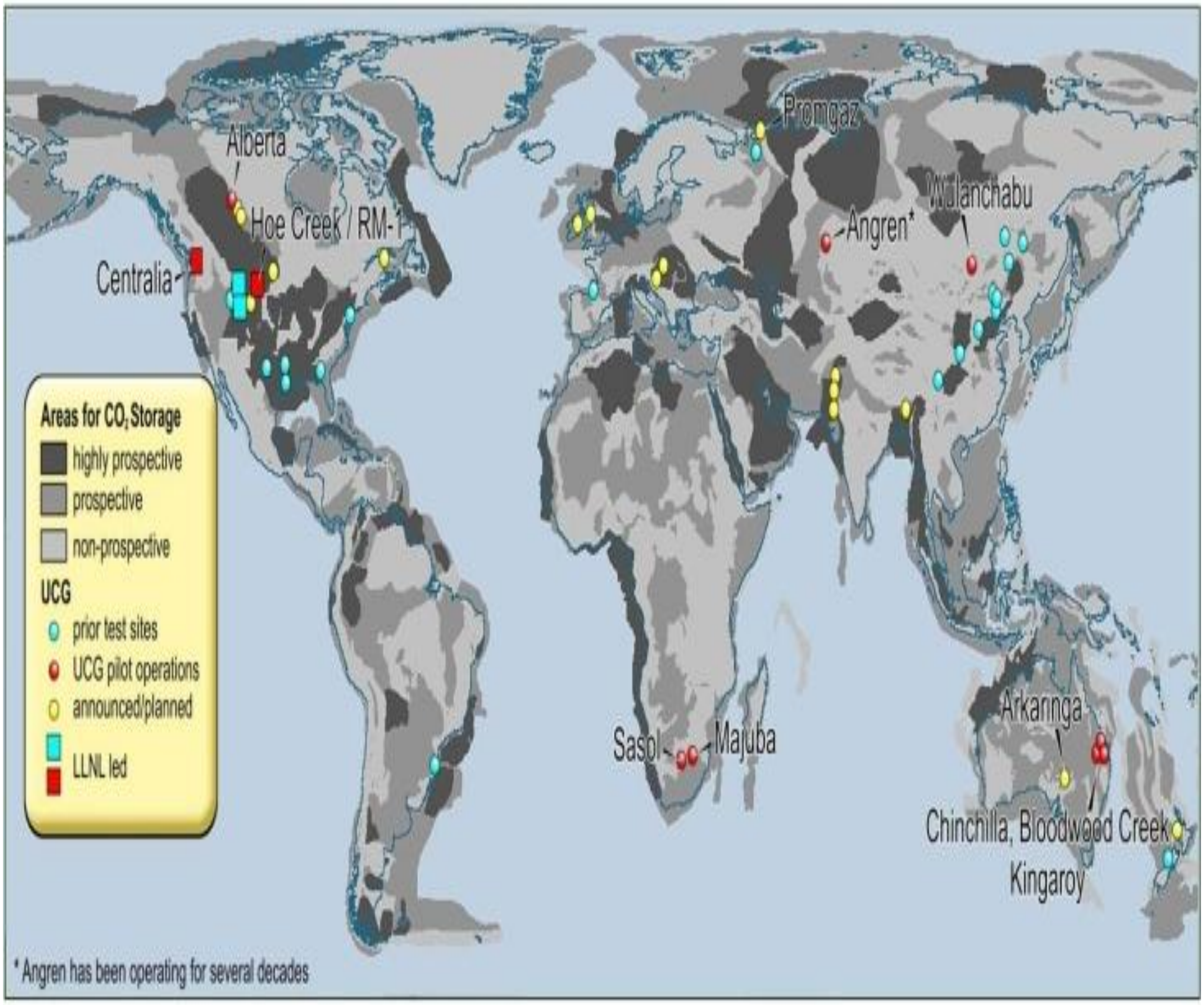


Fig. 13: Cost of UCG power generation

XIV. UCG PROJECTS WORLD WIDE

The basic knowledge of the UCG process existed for more than 100 years, but the process in development was undertaken by National program of research work from over 50 years in Western Europe, the United States, the former Soviet Union, to some extent in China, and Australia. For more than 40 years, commercial size project has been operated at the former Soviet Union, in western part all these projects were not led as a commercial project, since then there are 60 and over UCG projects throughout the world [12]. There are since been an increasing number of UCG projects emerging around the world including Australia, UK, Canada, USA, India, Vietnam, Pakistan, Hungary, Chile and South Africa as shown in the Fig. 14 [10].



Source: http://www.iea-coal.org.uk

Fig. 14: UCG technology in different parts of the world [10]

XV. CONCLUSION

The UCG method of gasifying the coal allows a revolutionary reformation of coal, as we know it could lead to the end of large scale underground and strip mining of coal in couple of years. World can use UCG method for coal deposits in spite of uneconomical way of extracting coal by mining. Coal can be used as the temporary building blocks of a renewable energy. To cope up with the shortfall of energy over the next half century coal mining can be replaced by UCG until the generation of renewable energy can commercially compete. In UCG process the unwanted green house gas (GHG) emissions spread in the atmosphere are minimal, and eliminates the harm. Carbon capture and storage of carbon dioxide technology can be used for enhanced oil recovery, and the further captured CO_2 can be stored in the underground saline reservoir.

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