Underground coal gasification from a Worldwide Point of View

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1. Introduction

The present imbalance between the consumption of certain fossil energy sources and the presence of corresponding extractable resources will alter the world energy market situation in the future. This is all the more true in that the regional distribution of developable deposit varies widely throughout the world. Table 1 shows the proved oil, natural gas, and coal reserves at the end of 1987. The Middle East holds in terms of the world's total proved reserves oil a dominant position. Two thirds of the world's natural gas reserves account the USSR and the Middle East. The world's reserves of coal are rather more evenly distributed around the globe. Nevertheless, the USA, the USSR, and China are endowed with very much larger reserves than any other area.

Today 60% of the world energy consumption are met by mineral oil and natural gas, while coal's percentage in meeting these needs amount to about 30%. In contrast the percentage of coal in the world's known, economically recoverable fossil fuel resources is 75%, whereas oil and gas deposits constitute only 20%. Actually existing geological coal supplies are approximately ten times that amount, a fact which underscores the special importance of this fuel and raw materials for the future. Tapping the deeplying coal deposits could multiply the coal reserves available for the future.

To accomplish at least partial utilization of deeplying coal deposits, a technology must be developed by which coal can be transformed in situ from the surface, into a product that can be recovered through boreholes. For the purposes of such so-called borehole mining, it is conceivable that in time procedures will be developed to convert coal into a gaseous, liquid, or fluidized aggregate state. The recovery of deep-lying coal deposits could become an economically feasible proportion due to low recovery costs, low environmental burden, and easy handling of the recovered product.

Of all methods currently being discussed for purposes of recovering coal deposits from the surface underground coal gasification is the only one to date that has reached the stage of experimentation and field tests.

2. Underground Gasification of Coal

The term "coal gasification" refers to the chemical conversion of coal into a combustible gas mixture by means of a gaseous gasification agent. The high temperatures necessary for this process are produced through partial combustion of the coal. Commonly used gasification agents are oxygen air, and sometimes blends of steam and carbon dioxide. The resulting raw product gas can be used as fuel gas for electrical power production or as a synthesis or reduction gas for the chemical industry.

The course of the gasification process and thus the composition of the product gas can be controlled, within certain limits, by adjusting such process parameters as pressure or composition and quantity of gasification agent used.

Underground coal gasification was first discussed more than 100 years ago, as for example in descriptions by C. W. Siemens in 1868, and by the Russian scientist D. I. Mendeleev in 1888. Systematic investigations including laboratory and field experiments commenced in 1928 in the Soviet Union, resulting in first attempts at large-scale application of this technology at shallow depth in the 1960s.
In underground coal gasification at great depth coal deposits are tapped by means of drilling. At least two boreholes are required: one for introducing the gasification agent and one for recovering the product gas.

In addition, communication must be established between the borehole, within the coal seam; such a communication is known as a linking pathway. For this purpose such procedures as hydraulic or explosive fracturing or counter-current tunnel combustion—so-called reverse combustion—could conceivably be used. The only procedure that has been applied with any success so far is tunnel combustion; the other technologies have not yet been developed to the point of technical feasibility. The establishment of such a communication, particularly at great depths, is a difficult undertaking and even today not entirely controllable. But with the application of so-called diverted drilling, a technology that has already been used successfully in recovering mineral oil and natural gas, it looks as though it will be possible to solve this problem in the future. Thus, in a recent Belgo-German field experiment two vertical boreholes spaced 35 m apart were linked through this method at a depth of approx. 850 m.

A general sketch of such a gasifier after a communication has been established by means of diverted drilling is given in Fig. 1.

Once an open or highly permeable pathway has been created within the coal seam the coal is ignited at the point of injection of the gasification agent and a reaction zone is formed along the path of the gas flow to the surface. This procedure is known as concurrent flow tunnel gasification.

Application of filtration gasification, where gases are supposed to flow through the coal bed under high pressure and without installation of artificial flow paths, proved impracticable.

### 3. Operated UCG Reactors

#### 3.1. Soviet Union

The USSR is most advanced as far as the technical application of underground is concerned. Among the five underground gasification plants having been operated, two are still in operation. These are the Angren plant sited on the lignite deposits of Central Asia near Taschkent and the Kiselevsk plant in the Siberian Kusnezk hardcoal field. Both have been operative for more than 25 years now. The Station Angrenskaia in Angren gasifies hard browncoal of a

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Table 1. Proved reserves of oil, natural gas, and coal (1987).

|                | Oil          | Natural Gas | Coal     |
|----------------|--------------|-------------|----------|
|                | Thousand | Natural Gas | Million | Share of total (%) | Share of total (%) | Share of total (%) |
|                | barrels   |            | tons     |                     |                      |                      |
| North America  | 41.1      | 8.1    | 270,421  | 4.6               | 7.5                 | 26.4               |
| Latin America  | 114.3     | 6.5    | 6,996    | 12.9              | 5.9                 | 0.7                |
| Western Europe | 22.4      | 6.2    | 95,568   | 2.5               | 5.8                 | 9.3                |
| Middle East    | 564.8     | 30.7   | —        | 63.0              | 28.5                | —                  |
| Africa         | 55.2      | 7.0    | 65,907   | 6.1               | 6.6                 | 2.5                |
| Asia and Australia | 19.5 | 6.3    | 94,488   | 2.1               | 5.9                 | 9.2                |
| Centrally-planned economies | 79.2 | 42.8 | 492,967  | 8.8               | 39.8                | 48.0               |
| Total World    | 896.5     | 107.6  | 1,026,147| 100.0             | 100.0               | 100.0              |
| OPEC           | 670.7     | 41.1   | —        | 74.8              | 38.3                | —                  |

![Diagram of deep-lying coal seam through diverted drilling](image)
shallow deposit (approx. 250 m) with air. The product gas is used for electricity generation in a power station. The Station Juzno-Abinskaja in the near of Kiselevsk gasifies hardcoal at depths down to 400 m with air as gasifying medium. The gas is used in a district heat supply unit. Three other plants are projected in the European, Siberian and Far Eastern part of the USSR. The long-term target is to extract 28% of the lignite and hardcoal reserves in the USSR by underground gasification.

3.2. USA

After the energy crisis in 1973 the United States conducted a number of field tests. The purpose of these experiments was to develop the technology of underground coal gasification to the point of economic applicability for the North American coal deposits. Nevertheless, the programme was limited to the recovery of deposits at depths of about 30 to 300 m.67

The Laramic Energie Technology Center (LETC) was able to demonstrate in six field tests conducted between 1973 and 1979 near Hanna, Wyoming, the technical feasibility of underground coal gasification in coal deposits of the U.S. Midwest. The coal that was gasified was a nonswelling subbituminous coal at a depth of 50 to 100 m.9 Under investigations were possible effects of the gasification process on the environment, the linking procedure known as reverse combustion, and the suitability of air as a gasification agent in the production of a slowly caloric product gas.

Three field tests were conducted by the Lawrence Livermore National Laboratory (LLNL) in Hoe Creek, Wyoming, in a moist, subbituminous coal seam, for the purpose of comparing various linking procedures and the compositions of a different gasification agents.10

Experience gained in the Hoe Creek tests led to the formulation of a new concept in underground coal gasification: the so-called controlled retracting injection point, or CRIP, method. In this procedure the gasification agent is introduced via a diverted borehole that has been fitted with piping and reaches down to the bottom of the coal seam, with the resulting product gas being drawn off via a vertical borehole. The coal is ignited a short distance away from the production borehole, and the gasification process continues unchanged until the caloric value of the product gas begins to drop. Then the inlet pipe is opened at some distance from the production well which permits the gasification agent to come in contact with fresh coal and thus reinitiates the entire process. Depending on the length of the inlet pipe and how far the injection point is retracted, this stage of the process can be repeated several times.

A series of short-term tests were carried out near Centralia by the Lawrence Livermore National Laboratory (LLNL) in cooperation with the Washington Irrigation and Development Company (WIDCO) in a mountainside coal deposit with the 10-m wide coal seam appearing as an outcrop on the mountain’s face. In the lower part of the coal seam horizontal pathways approx. 30 m in length running through the seam served as injection inlets while vertical boreholes served as outlets for the product gas.11 In the final test the crp concept successfully applied.

Following the test series an experiment lasting more than 30 days was conducted in the same coal deposit, providing additional information with regard to the applicability of the CRIP method.12

This CRIP maneuver had the effect of considerably increasing the calorific value of the product gas, which until then had shown a tendency to decrease, for a period of 8 days after maneuver was performed. Variations in composition and amount of gasification agent had only a slight effect on the gasifier; in comparison with other changes in parameter, modifications in the gasifier’s geometry due to obstruction by bits of coal or rock as well as the change in the point of injection created by the CRIP maneuver had far more noticeable effects on process development.

Near Pricetown, West Virginia, the Morgantown Energy Technology Center (METC) tested in 1979 the applicability of underground coal gasification with so-called Eastern coal. This is a bituminous coal with a marked tendency toward swelling and agglutination, occurring at a depth of 300 m in relatively narrow seams.13

Attempts to establish a communication pathway inside the seam by means of diverted drilling had to be abandoned because of technical problems. Using the method of reverse combustion at high differential pressures it was possible to create a pathway between three vertical boreholes.

In two tests performed near Rawlins, Wyoming, the underground coal gasification process was applied in steeply inclined, subbituminous coal deposits by the Gulf Research and Development Center.1415 The coal seam was tapped in direct drillings where the production borehole ran through the seam from the surface while the injection drilling was at a wider angle, reaching the seam at a depth of about 120 m.

In the gasification phase a variety of mixtures of air, steam and oxygen were used; use of a steam-oxygen mixture resulted in high-quality product gas. Thus, over the course of the 66-day Rawlins II gasification phase, over 7 500 t of coal were converted in gas, with a mean caloric value of 12 MJ/m³.

The positive results of Rawlins II show that a steeply inclined deposit can be favourable to application of underground coal gasification.

In 1978 the Atlantic Richfield Company conducted a field test in a deposit of subbituminous coal near the town of Rocky Hill, Wyoming. The deposit was located at a depth of approx. 200 m, with a seam width of 30 m.16

Three vertical boreholes spaced 23 m apart were linked through reverse combustion; only one pair of boreholes was used for gasification purposes as there were delays in establishing the second linking pathway. Air was the only gasification agent used, and over the course of a gasification phase lasting nearly 60 days over 3 200 t of coal were converted into a high-quality product gas.
Between 1987 and 1988 the "Rocky Mountain 1" field project was carried out in Hanna, Wyoming. The experimental programme was sponsored by the Department of Energy and an industrial consortium under the leadership of the Gas Research Institute and the executive management of Stearns Catalytic Corporation. During the test, two underground coal gasification technologies were demonstrated simultaneously. The first technology was Controlled Retracting Injection Point, CRIP. This technology was successfully demonstrated on a commercial scale, with three CRIP maneuvers being performed and subsequent gasification reactors being developed. In this part of the test, about 11,000 t of coal were gasified over the 102 days. The second technology was the Extended Linked Well, ELW, which is a modification of the linked vertical well concept that has been used in most UCG tests to date. This approach involves drilling a series of vertical wells into the coal seam for the ignition of successive coal zones. The ELW module operated for 45 days with initial injection well producing quality gas. Over 4,000 t of coal were gasified over a distance of 30 m.\(^{17}\)

### 3.3. Research Activities for Application of Underground Coal Gasification in Western Europe

In the early 1970s the interest in underground coal gasification was reawakened in West Europe and a number of research and development projects were conducted in Belgium, Germany, France, Great Britain, and the Netherlands. Great Britain and the Netherlands have conducted only theoretical studies and laboratory experiments, while Belgium, Germany, and France were carried out three field tests to date.\(^{18}\)

In France, from 1979 to 1984, GEGS (Groupe d'Etudes de la Gazéification Souterraine), a working group constituted by four companies and governmental agencies (Chrabonnages de France, Gaz de France, Institut Français du Pétrole and Bureau de Recherches Géologiques et Minières) conducted two field tests in depth between 800 and 1,200 m.\(^{19,20}\)

In Bruay-en-Artois, starting from a shut-down coal mine, two vertical wells spaced 65 m apart were drilled into a seam lying 200 m deeper down. Through application of hydraulic fracturing with up to 500 bars of fluid pressure and use of mixtures of water and sand permeability between boreholes could be increased such that a slight gas flow could be maintained throughout the seam. Successful attempts to create a highly permeable pathway between boreholes through reverse combustion had to be prematurely abandoned because of the occurrence of spontaneous ignition within the coal seam in the injection drilling zone as well as due to various technical problems and the high cost of mine operation and maintenance.

The second field test was conducted in the coal mining district of Nord-Pas de Calais in Haute-Deule; here two vertical wells 60 m apart were drilled from the surface down into a coal seam located at a depth of 880 m. After successful hydraulic fracturing, during the successive phase of reverse combustion spontaneous ignition of the coal was largely prevented by the addition of carbon dioxide to the gas stream. Following a reverse combustion phase lasting 50 days, problems in the process wells resulted in the termination of the experiment before a permeable pathway could be created; in neither of the experiments was it possible to carry out a gasification phase. GEGS's plan to establish a direct communication between two vertical wells via a third borehole starting from the surface and running through a 9- to 20-m-thick coal seam at a depth of 800 m could not be further pursued for lack of funds.

The French field project was accompanied by laboratory and model projects carried out by the companies belonging to GEGS. The Institut Français du Pétrole conducted investigations on spontaneous ignition and reverse combustion and on electrolinking.

Near the town of Thulin, Belgium, a joint Belgo-German field project has been in progress between 1979 and 1988, under the direction of IDGS (Institution pour le Developpement de la Gazéification Souterraine).\(^{3,23}\)

Four vertical wells, 33 m apart, were drilled down to a coal bed approximately 860 m deep and 2 m thick. Attempts to link the wells by means of reverse combustion under high differential pressures failed because of the coal's lack of natural permeability and its tendency toward spontaneous ignition under high gas pressure. In addition, the extreme conditions underground, i.e., the required changes in temperature and the presence of corrosive gas, made for considerable problems with regard to the materials used for piping.

In early 1986 the connection between the injection and production well brought about rather by a diverted and horizontally directed borehole. Due to the short distance between the existing vertical boreholes the linkage drilling had to be done with a radius of 12 m. This created some inconveniences which prevented normal ignition at a well-defined point so that not precisely delimited reaction chamber took shape. Nevertheless, it was possible to get a conversion reaction started in the deposit and to maintain it for 200 days.

Table 2 is a list of the main operative plants and field tests implemented worldwide so far and which reflect the present state of the art.\(^{7}\)

### 3.4. Future Procedure of Underground Coal Gasification

In the USA a plant for the production of urea and ammonium (500 t/d, Rawlins, Wyoming), where gas from the underground gasification of a stuby dipping seam will be used, is scheduled to take up the production during 1989. If the project turns out successful it is planned to build and operate a plant relying on the Fischer-Tropsch synthesis for production of Diesel and carburetor fuels.\(^{17}\)

India's Oil and Natural Gas Commission (ONGC) has been planning a pilot test for the gasification of deep hard brown coal (at 870 m depth), to be followed by a commercial large-scale project.\(^{7}\)
The Department of Energy of New Zealand intends to commence with the preparations of a pilot test based on the state of knowledge acquired in the USA. A shallow lignite deposit at a depth of about 200 m, contained in seams of approx. 5 m thickness is to be gasified under the project. After successful completion of the test the plant is to be transformed into a large-scale commercial unit.

4. Theoretical and Experimental Studies in Europe

4.1. Great Britain

The National Coal Board (NCB) has been conducting theoretical and practical development work preparatory to a field test. The result of these studies is that the coal deposits should be tapped by means of diverted drilling within the seam at depths from 500 to 1 000 m, and that gasification under high pressure using mixtures of steam and oxygen as gasification agent is advantageous. At present the main focus of the NCB studies is on developing a drilling procedure where permeability is controlled by measuring the natural gamma radiation of the coal and the adjoining rock. For this project a seam with a thickness of 2.5 m was selected. A diverted, horizontal tunnel running through the seam for a distance of approx. 300 m serves to initiate the gasification process. This tunnel is linked with three vertical wells spaced about 100 m apart. The project is currently at the stage of being granted official approval.

4.2. The Netherlands

In the Netherlands there are long-term plans for an underground coal gasification programme, divided into three phases. Phase I includes studies and laboratory experiments, as well as the elaboration of alternative concepts, and should be concluded by 1990. Phase II comprises field tests backed up by laboratory experiments over the period 1990 to 1995. Phase III (from 1995 on) foresees a pilot project. However, nothing has yet been decided with regard to the kind of project within the framework of Phases II and III. Most of the work currently in progress is being carried out at the Technical University of Delft, with laboratory experiments being backed up by the theoretical investigations. These investigations are concerned with heat transfer processes, measurement of heat losses, and finite element calculations to determine the development of rock fragments in the overlying stratum.

4.3. Other European Activities

The possibility of implementing underground coal gasification in Spain is being examined in a provisional study that is being carried out with assistance from an American company, Energy International.

Studies on the application of underground coal gasification using coals with a high ash content are also being conducted in Yugoslavia.

4.4. Federal Republic of Germany

Work using funds from the Federal Ministry for Research and Technology has been in progress in the field of underground coal gasification since 1975. This work commenced with the Aachen Project, which provided for the establishment of a UCG laboratory and investigations of gasification with particular attention to changes in pressure.

From 1976 to 1978, the Saarberg-Interplan Company put together requirements with regard to coal deposits for conducting field tests in the West German region of Saarland, selecting and identifying possible test locations. It also developed a core bit for taking compact coal samples.

Messerschmidt-Bölkow-Blohm conducted a system study investigating the various methods of measurement available for use in the gasification process.

In 1977 a mathematical model to describe underground processes began to be developed at Bergbau Forschung GmbH in Essen. In its first stage the model merely gave a description of a gasification process using hydrogen as gasification agent. Successful application of the model in the area of oxidizing gasification was not possible due to numerical
instability problems.

Since 1979 the Saarland University has been examined the behavior of coal under the influence of different temperatures and pressures, emphasizing volume and gas permeability behavior at temperatures of up to 700°C in a fluidic pressure system of up to 180 bars. In addition, studies have been in progress since 1984 to investigate the behavior of linking pathways under simulated overburden pressure conditions.\(^\text{30}\)

At the Technical University of Clausthal studies on methods to increase coal permeability have been in progress since 1982. It was possible to create gas flow paths in lignite by means of electro-osmotic drainage, while extraction using supercritical CO\(_2\) was not successful.\(^\text{31}\)

In 1982 a scientific research organization, Stuani- gesellschaft Kohlegewinnung Zweite Generation e.V.,\(^\text{21}\) was founded to initiate, coordinate, and implement fundamentals research in the field of coal conversion, with the objective of finding realistic development guidelines for the recovery and utilization of deep-lying coal deposits. The organization also views it as one of its responsibilities to organize seminars for an interdisciplinary comparing of notes. Two research projects have been started to date. A study gathering data on the properties of deep-lying coal deposits and adjoined rock for the purpose of bringing about in situ coal conversion reactions has already been concluded.

A second project is being launched to classify different coals with regard to their geologic and tectonic position inside coal deposits from the perspective of in situ conversion reactions.

At the Institute of Ferrous Metallurgy at the Aachen University of Technology, with backing from the Federal Ministry for Research and Technology, work has been in progress since 1975 to develop and test possible procedures for in situ gasification of coal.\(^\text{32,33,34}\)

In investigating the gasification process it is not possible to take into account the complex interrelationship between all the influencing factors in a single system. Therefore, in view of the requirements of the problems to be solved, different laboratory instruments have been designed, constructed, and put into operation to allow the exploration of one or more problems. Table 3 is a list of the different laboratory apparatus.

Material and process data have been gathered or established experimentally within the context of fundamentals research by means of laboratory tests to investigate elementary physical and chemical processes.

Among the areas investigated are the followings:
- Degasification or pyrolysis of different kinds of coal at defined heating-up speeds and process pressures between 5 and 60 bars.\(^\text{35,36}\)
- Kinetic of oxidizing gasification with air or mixtures of air and steam, and hydrating gasification.\(^\text{34,36}\)
- Problems presented by spontaneous ignition of coal, which can result in an obstruction of existing gas flow paths, especially in tunnel combustion.\(^\text{37}\)
- Permeability of coal and adjacent rock to gas.\(^\text{38,39}\)
- Reverse combustion.\(^\text{40,41}\)
- Corrosion simulations on materials of the well equipment.\(^\text{42,43}\)

In Aachen tests were done, e.g. in the large pressure autoclave (see also Table 3, No. 8), Fig. 2, and in the large scale apparatus (see also Table 3, No. 9), Fig. 3.

5. Conclusion

The results of field tests and laboratory experiments conducted to date can be summarized as follows:

| Reactor type | \(P_{\text{max}}\) (bar) | \(T_{\text{max}}\) (°C) | Sample size | Sample weight | Subject of investigation |
|--------------|----------------|----------------|-----------|---------------|------------------------|
| 1. Glass-reactor | 1 | 1200 | \(\phi : 10\) mm | 2 g | Reaction kinetics |
| 2. Gram-autoclave | 100 | 1200 | \(\phi : 10\) mm, \(L : 20\) mm | 2 g | Ignition point, DTA |
| 3. Permeameter | 200 | — | \(\phi : 30\) mm, \(L : 20\) mm | 40 g | Permeability |
| 4. Pipe-reactor | 1 | 1000 | \(\phi : 50\) mm, \(L : 50\) mm | 1 kg | Reverse combustion, Self ignition |
| 5. Small autoclave | 60 | 1000 | \(\phi : 200\) mm, \(L : 400\) mm | 15 kg | Permeation, Pyrolysis, Corrosion |
| 6. Overburden-pressure Simulating apparatus | 500 | 200 | \(\phi : 200\) mm, \(L : 400\) mm | 28 kg | Process simulation |
| 7. 1 m-Autoclave | 100 | 1000 | \(\phi : 200\) mm, \(L : 1000\) mm | 38 kg | Reverse combustion, Pressure swingung |
| 8. Large pressure autoclave | 60 | 1000 | \(\phi : 320\) mm, \(L : 4000\) mm | 386 kg | Process simulation |
| 9. Large scale apparatus | 1 | 200 | \(L : 10\) m, \(B : 1.7\) m, \(H : 0.4\) m | 7000 kg | Long burnfront-behaviour |
- Countercurrent tunnel combustion, used to create linkage pathways in coal seams, is unsuitable for overcoming distances of 30 m and more. Problems can arise due to low gas permeability in coal deposits and the risk of spontaneous ignition.  
- As yet deviated drilling is the only certain method for establishing communications within coal seams.  
- Directed ignition by means of controlled spontaneous ignition appears to be a possibility; however this procedure is not yet fully controllable.  
- The complex stress on materials presented by the corrosion of the well equipments during the various phases of UCG in great depth calls for precise reproducibility of the damages that has occurred. In the reset stage materials to be used for this application should be examined.

The objective and task of further research activities is to examine coal, and especially coal occurring at great depth, with regard to its potential for gasification. This means investigating highly coalified coals and determining the optimum composition of gasification agents. The interplay between degasification of coal and gasification of the coke resulting from this process needs further explanation. Depending on what process stage has been reached in the linking or gasification process, it also is necessary to activate (i.e., through locally or temporally directed ignition inside coal seams) or to inactivate (i.e., by avoiding spontaneous ignition) certain areas of the coal seam. This requires technologies having an influence on low-temperature oxidation kinetics. The special conditions presented by coal seams at great depths should be taken into account in selecting the gasification procedure to be used. Progress of the gasification front essentially against the line of gas flow guarantees that the gasification agent will always come into contact with fresh coal first.
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