Feasibility study on underground coal gasification of No. 15 seam in Fenghuangshan Mine

by W.G. Huang*†, Z.T. Wang*†‡, L. Xin*†, T.H. Duan*†, and G.J. Kang‡

Synopsis

To recover the coal resources of high-sulphur anthracite in Jincheng Mining Area, underground coal gasification (UCG) of No.15 seam in Fenghuangshan Coal Mine was proposed. The feasibility of the project was confirmed by investigations of occurrence conditions, coal properties, and roof conditions, as well as experimental studies and theoretical analysis. It was found that UCG technology is appropriate to be adopted in the mining of the No. 15 seam, due to the stable rock conditions, simple geological structure and hydrogeology, the high carbon content of the coal, non-cohesiveness, medium-thermal stability, high ash fusion temperature, and weak reactivity with CO_2. Further factors are the characteristics of the immediate roof, which consists of 9.11 m of limestone and mudstone with a compact structure and low permeability, and 4.27 m of dominantly mudstone with low permeability.

Keywords
No. 15 coal seam, underground coal gasification (UCG), galley-type UCG, occurrence conditions, coal properties, surrounding rock conditions.

Introduction

Underground coal gasification (UCG) is a promising technology as it is a combination of development, mining, and gasification. As a future technique for utilizing coal resources, UCG has environmental and other advantages over the conventional mining process, which include higher coal resource recovery, better economic performance, higher utilization ratio, increased worker safety, and more friendly to the environment[1]. Furthermore, UCG can not only recycle abandoned coal resources, but can also be utilized in the thin seams, deep seams, coal seams under railways, buildings, and water, or with coal with high contents of sulphur, ash, and methane, which are difficult, unsafe, or uneconomic to exploit using traditional methods.

High-sulphur anthracite, a type of highly metamorphosed coal, makes up a quarter of the entire reserve in Jincheng Mine Area of Shanxi Province, China. For a long time, it was not feasible to exploit this material due to its high sulphur content, and it eventually became a dormant resource. In order to exploit the high-sulphur anthracite, increase the utilization of the resources, and resolve the development of the old mine, the project to recycle the No. 15 coal seam in Fenghuangshan Coal Mine utilizing galley-type UCG technology was proposed.

Liang *et al.*[2] investigated the feasibility of UCG in the Fuxin mining area, but omitted any analysis of the conditions at the mine, neither was any experimental work conducted. Although researchers have studied UCG models for various mineral projects, none have confirmed the feasibility of UCG technology under the prevailing resource conditions[3–6]. In this paper, we present a comprehensive investigation of the feasibility of UCG at Fenghuangshan Mine using field research, trial studies, and theoretical analysis, taking into consideration the characteristics of the coal seam, coal properties, and surrounding rock conditions.

Conditions of coal seam

Characteristics and reserves of No. 15 coal seam

The No. 15 seam at Fenghuangshan Mine lies at a depth of 100–400 m, with dip of 2°–15°, thickness 1.60–5.50 m (average 2.33 m), 29 m beneath the No. 9 seam. Successful field trials of UCG in different countries, including the Yuzhno-Abinskaya, Angrensikaya, Podmoskovnaya, Chinchilla, and Tremedal trials[7], have been conducted at depths between

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30 m and 580 m, and with seam thicknesses from 2 m to 5 m. Obviously, the No. 15 coal seam meets these requirements. However, in cases where the dip of the coal seam is less than 15°, the roof will quickly collapse if the longwall gasification face is utilized, particularly if the stability is poor. In addition, the heat source in the underground gasifier will be quenched easily because the coal seam is isolated from gasifying agents by liquid slag, which is converted from coal at high temperature and may form a covering layer on the surface of solid coal, particularly when the coal seam is horizontal. To avoid this, the inclined shortwall face method should be applied so that the combustion front advances from bottom to top during exploitation.

The total reserve of No. 15 coal seam is about 87.97 Mt, including 40.63 Mt of high-sulphur coal is and approximately 47.34 Mt of non-high-sulphur coal .

Geological structure

The geological condition of the coal field is fairly simple. A large NNE trending reverse fault termed F_1 forms the western boundary of the coal field. Due to east-west compressional movement, the structure in Fenghuangshan Mine is mainly open folds consisting of regularly-spaced anticlines and synclines, whose axes are near-parallel to fault F_1. Moreover, there are some minor faults with a throw of less than 5 m and medium-to-small scale collapse columns in the coal seam. In the process of designing the project, the underground gasifier should not be situated in areas studded with faults and collapse columns in order to avoid gas leakage and water inrush, which would in severe cases disrupt the gasification process. The type of wells used in UCG can effectively prevent those accidents, because the structure will be elucidated during tunnel excavation and the appropriate mitigating measures can be adopted. Protective coal pillars should be retained when major structures are encountered, particularly faults with a throw of more than 5 m and large-scale collapse columns. The geological structure is illustrated in Figure 1.

Hydrogeology

The Siyi and Chequ rivers, which are located in the north and south of the mine area respectively, are both seasonal. Most of the reservoirs and ponds, which are small-sized, contain no water all year round due to drought and many years of disrepair, except during the wet seasons. The surface water is isolated from No. 15 seam by the thick argillaceous aquifuge and waterproof pillars remaining in the No. 3 and No. 9 seams.

In the coal field, No. 3 seam has been stoped out and No. 9 partially stoped out. Both goaves have water to a varied extent. There is a distance of about 64 m between coal seam No. 3 and No. 9, which is about 29 m away from No. 15 seam. Generally, there will be no hydraulic interaction, but while the large area of No. 15 seam is being mined, the caving zone or fracture will reach the gob floor in No. 3 and No. 9 seams, then the goaf hydrops will pour into the working face of No. 15 seam along the fracture.

The K_2 limestone stratum is one of the main aquifers in the coal field, most of which is at a depth of 110-360 m. It is characterized by compact structure, undeveloped fracture, and weak water bearing property, and has little influence on the exploitation of No. 15 seam. The water level in the Ordovician karst limestone is an altitude of 579 m. Mining below this level in No. 15 seam will therefore be under pressure. Nevertheless, because of the mudstone with a thickness of 4.06 m–22.25 m (mean 8.65 m) on the basal surface of weathering of the Ordovician limestone, which is a good aquifer, the probability of water inrush is very low, except in areas where there is structural communication.

According to the comprehensive analysis of the hydrogeology and the water filling factors in the mine, the hydrogeology of No. 15 seam is simple in most areas, and in some areas under pressure is of intermediary type. A conventional longwall advancing mining method would cause the roof of the mined area to fall to a great extent, and the fractures may connect the water-accumulated gob of No. 3 and No. 9 seams or floor aquifer, which would be likely to result in water intrusion into the underground gasification

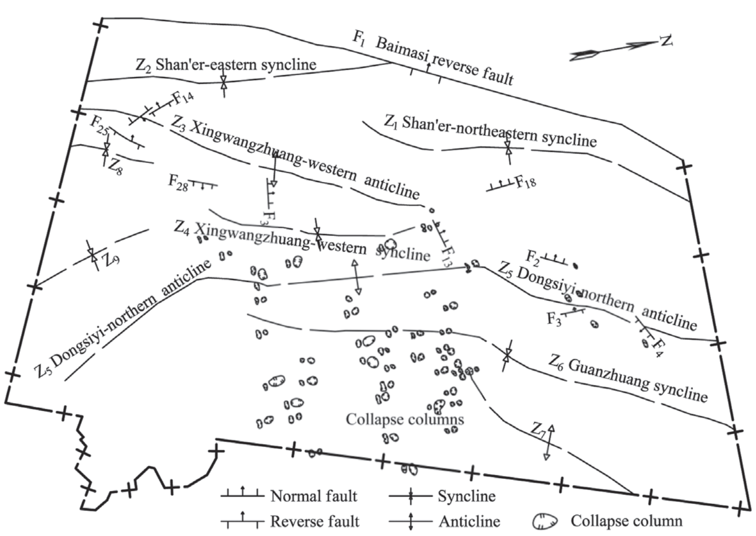


Figure 1—Geological structure of Fenghuangshan coal mine

working face and even interrupt the gasification process. The shortwall face mining method should therefore be utilized to guarantee the integrity of the roof. A small amount of water inflow would cause very little harm to the flame working plane, because an appropriate amount of groundwater can promote the water gas reaction and increase the gas calorific value.

Coal seam gas

In China most of the coal seams are gas coal seams to different degrees[8]. Studies have proven that coalbed gas content is positively correlated with metamorphic grade, depth of burial, and the coal measure stratum thickness[9]. Although anthracite is characterized by a high level coalification, the No. 15 seam is shallow and the stratum thickness is low (mean 83.23 m), both of which mitigate against the accumulation of methane. According to the actual exploitation conditions at the nearby Wangtaipu Coal Mine, the absolute outflow of gas from No. 15 seam is 0.08–0.26 m^3/min, much lower than 40 m^3/min, therefore it is a low-gas coalbed. Coal gas, also called coalbed methane (CBM), is a relevantly clean source of energy, and should be fully utilized. When the gas coal seam is exploited with the UCG technology, gas would be extracted before gasification as a lot of long, large-diameter boreholes will be drilled in the coal seam. However, the coal and gas could be gasified together without pre-drawing of the gas. In 2005 co-gasification in a high-gas mine was carried out successfully by China University of Mining and Technology in the Zhongliangshan Coal Mine, Chongqing[10].

Coal properties

Coal type and petrology

The coal type of No. 15 coal seam is anthracite, whose main petrographic constituent is bright coal, with lesser amounts of semibright and semidull coal, and a small amount of dull coal. The UCG field tests at the Donbass mines in the former Soviet Union indicate that the optimum coal types for underground gasification are lignite, flame coal, lean coal, and anthracite, and the bright and semibright coal are more propitious for the gasification process than the semidull and dull coal[11].

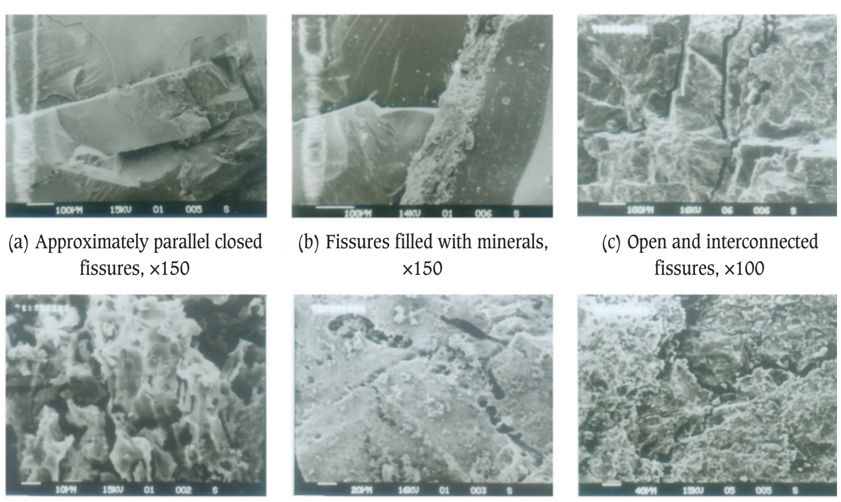
Characteristics of fissures and pores

The more and bigger the microfractures in the coal seam, the greater the permeability and the faster the gasification. The characteristics of fissures and pores of the anthracite is therefore of prime importance. Since the 1970s, properties of fissures and pores in coal have been investigated closely both in China and abroad, and classified by observing the microstructure by the scanning electron microscope (SEM), and their effect on gas outbursts and CBM production investigated[12,13]. In this study, the coal microstructure was studied using the SEM to determine whether it is suitable for gasification. The results are shown as Figure 2.

The SEM investigation showed that the fissures in the anthracite in No. 15 coal seam are well developed and interconnected, and mostly closed or with small opening, with only few with large opening and filled with minerals. The pores some areas of the anthracite are well developed, with diameters chiefly between 1 μm and 10 μm. Although a few pores have good connectivity with each other, this contributes little to the coal reservoir permeability. The fissures and pores in the coal and rock mass have different porosities and permeabilities. The fissures have low porosity and high permeability, so they always act as the transmission channel for the fluid. In contrast, the pores have high porosity and low permeability, and act as the storage medium. Although the fissures in No. 15 seam are fully developed, most of them are tight fractures or with a large opening and are often filled with minerals, which results in the limited ability of the coal stratum to transmit fluid.

Proximate and ultimate analysis

The proximate and ultimate analysis of anthracite in No.15 coal seam in Fenghuangshan Coal Mine is shown in Table I.



(a) Approximately parallel closed fissures, ×150

(b) Fissures filled with minerals, ×150

(c) Open and interconnected fissures, ×100

(d) Interconnected pores, ×700

(e) Pores filled with minerals, ×400

(f) Network of pore and fissures, ×290

Figure 2—SEM micrographs of fissures and pores in anthracite

Table I

Proximate and ultimate analysis of anthracite of No. 15 seam

Proximate analysis (%)				Ultimate analysis (%)					Gross calorific value (MJ/kg)	Low calorific value (MJ/kg)
Mad	Aad	Vad	FCad	Cdaf	Hdaf	Ndaf	Odaf	St.d		
1.97	19.18	6.70	73.50	93.06	2.92	0.89	2.20	3.55	31.74	30.90

ad: Air dried basis; daf: Dry ash free basis; St.d: total sulfur contented in coal, which includes organic and inorganic sulfur

The results indicate that No. 15 seam is characterized by high content of fixed coal and sulphur, and low water, ash, and volatile content. From this it may be supposed that the anthracite of No. 15 seam has a high gas production rate and sulphide concentration in the gas, so desulphurization treatment should be conducted during gas purification. However, the levels of tar and light hydrocarbons will decrease for low-volatile anthracite, which will reduce the gas calorific value. Furthermore, with low moisture content, the water will be transformed into steam and decomposed to H_2 and O_2 in the process of gasification, which will increase the gas calorific value. Ash, an inert substance, does not join the gasification reaction. A low ash content can decrease the loss quantity of carbon which contained in the ash during the gasification process.

Carboxy reactivity of coal

Carboxy reactivity of coal refers to the coal's ability to reduce CO_2 to CO at a certain temperature. The higher the rate of reduction of CO_2, the stronger the coal activity. Carboxy reactivity was determined as follows. The coal samples were dry-distilled to eliminate volatile matter, then the carbonized coal particles were sieved and about 300 g of the 3–6 mm size fraction were placed in a reaction tube. The tube was heated at a rate of 20–25°C per minute until the temperature reached 750°C (conversion to lignite) or 800°C (conversion to bituminous coal and anthracite). The temperature was then kept constant for 5 minutes while CO_2 was pumped in at a flow rate of 500 mL/min at atmospheric pressure (1 013.3± 13.3 hPa) and room temperature (12–28°C). The flow of CO_2 was then shut off and after 2.5 minutes the CO_2 content of the gases produced by the reactions was measured while further increasing the furnace temperature at a rate of 20–25°C per minute until a temperature of 1100°C was reached. The CO_2 concentration was determined at every 50°C temperature interval[14]. From the CO_2 content at different temperatures, the relationship between the reduction rate of CO_2 and temperature was determined according to Equation [1].

$$\alpha = \frac{100(100-a-V)}{(100-a)(100+V)} \times 100 \qquad [1]$$

where α is the reduction rate of CO_2(%), a is the content of impurity gases in the CO_2(%), and V is the CO_2 concentration in the gases after reaction (%).

We tested the reactivity of No. 15 seam anthracite to CO_2 and compared the results with those of lignite, natural coke, and coking coal. It was found that, at the same temperature, the CO_2 reactivity of anthracite in No. 15 seam is the weakest, followed by coking coal and natural coke, with lignite being the strongest, as illustrated in Figure 3. This is mainly because the coal activity will decrease as the coalification increases. The project practice of surface coal gasification shows that the higher the activity of coal is, the shorter the time to reaction equilibrium and the lower the initial temperature of reaction and the gasification temperature, which will reduce the oxygen consumption, and *vice versa*[15]. The low activity of anthracite is thus unfavourable for the gasification of No. 15 seam coal. However, according to the laboratory trial, we found the reactivity of the anthracite is very weak at the low temperature, although as the temperature increases, the activity will obviously strengthen. Thus, the gasifier temperature could be raised by increasing the oxygen concentration in the gasification agent to enhance the anthracite activity, so as to improve the calorific value of the gas and the gas yield per unit volume of gasifying agent, and realize stable production[5].

Caking properties, thermal stability, and ash fusibility

Caking property refers to the coking performance of pulverized coal, after the stage of plastic mass production, by airless heating. Char residue characteristic[1–8] is commonly used as the index of the caking property of coal. The larger the index, the stronger the caking property. If the caking property of coal in gasification is too strong, the coal will cake into blocks and prevent the uniform distribution of the gasification agent in the underground gasification working face, which will have a negative effect on the gasification process. According to the result from the test of volatile determination, the anthracite in No. 15 coal seam belongs to type 1, which means the caking property is the poorest.

Thermal stability refers to the coal's capacity to maintain its original size at high temperature. Coal with good thermal stability is difficult to break during the gasifying process,

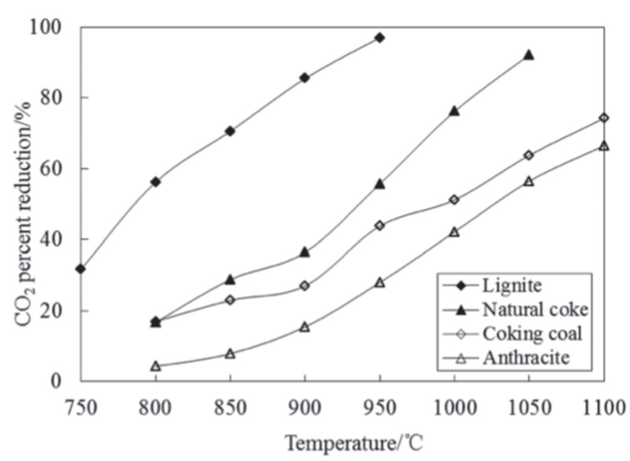


Figure 3—The carboxy reactivity curves of different types of coal

whereas it will readily break into pieces or powder if the thermal stability is poor. For surface gasification, fragments and dust easily induce slagging in the furnace, increase the resistance and the carryover, and decrease combustion or gasification efficiency, thus damaging the whole gasification process, even to the extent of interrupting the running of the gasification furnace. Therefore, coal needs to have enough thermal stability for above-ground gasification. However, in the process of UCG, if the coal face breaks and collapses quickly after being heated, the moving velocity of the flame working plane will be increased. According to the national standard[16], TS_{+6} is taken as thermal stability index, that is the percentage of residual coke weight in the 6 mm size fraction in the total weight of residual coke of all ranks after heating in the air-isolated muffle furnace at 850±15°C for 30 minutes. The thermal stability of anthracite from Fenghuangshan Mine was determined to be TS_{+6}=68.09 per cent. Based on the grading standard of thermal stability[17], with TS_{+6}>60%-70%, the No. 15 seam is coal of medium thermal stability, which is amenable to UCG.

Ash fusibility is a method of judging the clinkering property of ash, and also the main quality index of gasification coal. We measured the ash fusibility of anthracite from No. 15 seam by the pyramid method. The results demonstrate that the ash fusion temperature is comparatively high, and the sphere temperature is higher than 1500°C, so the anthracite belongs to the category of non-melting ash coals. This implies that it is not easy for the coal ash of No. 15 coal seam to slag. This is mainly because the contents of acidic oxides (SiO_2, Al_2O_3, and TiO_2) are high, making up 73.25 per cent of the total oxide content, while the content of basic oxides (Fe_2O_3, CaO, and MgO) is only 23.76 per cent, which leads to the high ash fusibility[18]. The analysis of the ash composition is shown in Table II.

Surrounding rock conditions

Roof and floor conditions

The immediate roof of No. 15 seam is the K_2 limestone, of which is 1.28-17.85 m thick (average 9.11 m) and stable. In the gasifying process, the limestone can decompose into CO_2 and CaO, which is favorable for UCG because the CO_2 will participate in the reaction and the CaO can absorb some sulphur compounds[19]. The immediate floor, with a thickness of 0.25–9.40 m (mean 4.27 m), is made up of compact mudstones and aluminous mudstones, and constitutes the main aquifuge preventing the ingress of water from the Ordovician limestone into No. 15 seam. UCG requires not only that the aquifuge in roof and floor should have good watertightness, but also favorable air tightness, because if the roof in the combustion space area collapses, water inflow and gas leakage can easily occur. To prevent this, further studies of the mechanical properties and permeability of the immediate roof are required.

Mechanical properties of immediate roof

The rock samples from K_2 limestone roof were processed into standard cylinder specimens with diameter of $50^{+0.6}_{-0.2}$ mm and height of 100 mm, 29 mm, and 50 mm for uniaxial compressive, tensile, and shearing tests, respectively. The compressive, tensile, and shearing strengths of the specimens were measured by an MTS815 type electro-hydraulic servo-controlled rock mechanics testing system. According to the results, the uniaxial compressive strength of the limestone is 63.09 MPa, the tensile strength is 6.67 MPa, the shearing strength is 19.67 MPa, the internal friction angle is 48.26°, and the cohesion is 6.26 MPa. The limestone is hard and this stratum will not cave easily.

Permeability of immediate roof

Microstructure of limestone

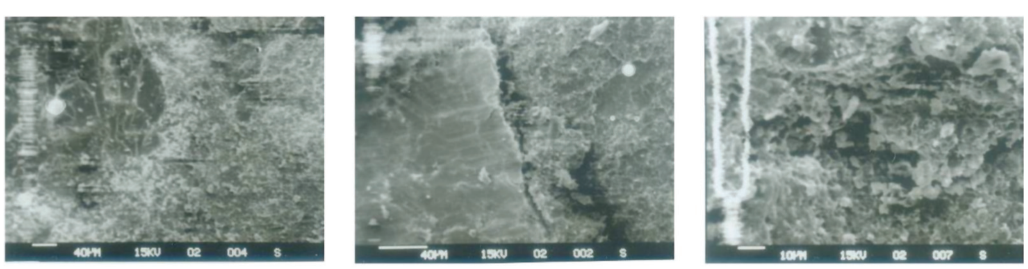
The microstructure of the samples from the K_2 limestone roof were investigated using a SEM (Figure 4).

The scanning patterns showed that the structure of the limestone constituting the No. 15 seam roof is compact, and the fissures are undeveloped. Pores in some areas are developed and dense, but most of them are shallow holes with poor connectivity. This indicates that the K_2 limestone roof has good integrality and poor permeability.

Table II

Ash fusion temperature and components of anthracite of No. 15 seam

Ash fusion temperature (°C)		Ash component (%)					
DT	ST	SiO_2 (%)	Fe_2O_3 (%)	Al_2O_3 (%)	CaO (%)	MgO (%)	TiO_2 (%)
1480	>1500	41.32	21.41	31.64	1.46	0.89	0.29



(a) Compact structure, ×200 (b) Fissure, ×400 (c) Dense pores, ×800

Figure 4–SEM micrographs of K_2 limestone

Permeability test of limestone

A complete stress-strain permeability test was carried out on two samples of K_2 limestone using an 815.02 type electro-hydraulic servo-controlled rock mechanics testing system. Rock blocks were made into specimens with a diameter of 50 mm and height of 60-80 mm as required. The test parameters and results are shown in Table III.

Jacob *et al.*[20] list some typical values of hydraulic conductivity and permeability of rocks, and classified the rock permeability and aquifer, as shown in Figure 5[20].

For comparison, the results in Table III should be converted and the results are shown in Table IV. The conversion from the darcy to area units is given by:

$$1Da = 1000\ mDa = 9.8697\text{x}10^{-9}\ \text{cm}^2 = 9.613\text{x}10^{-4}\,\text{cm/s}\ (\text{for water at } 20°C) \qquad [2]$$

Comparing the results in Table IV and the values in Figure 5, we find that –lg k > 6, -lg k > 11, and lg k <0. So it can be concluded that the samples belong to the impervious rock group, and the K_2 limestone stratum can be considered as a proof aquifuge.

Conclusions

The No. 15 seam is stable, with a depth of 100-400 m, dip angle smaller than 15°, average thickness 2.33 m, and low gas, and the geological structure and geohydrology is simple-medium. A new mining method, the man-made gallery style UCG combined with shortwall mining method, can be adopted to prevent the gasification working face from being submerged by the water from goaf and aquifers through fractures, faults, or collapse columns.

The anthracite from No. 15 seam, mainly composed of bright coal, has a low permeability though fracture development according to SEM observations, and has high contents of fixed carbon and sulphur but low moisture, ash, and volatilization. In addition, the tests indicate that the anthracite has these features: non-caking property, medium thermal stability, high ash fusion temperature, and weak reactivity with CO_2 which can be strengthened by the technique of oxygen-rich gasification to achieve stable yield.

The immediate roof of No. 15 seam consists of limestone and mudstone with a thickness of 9.11 m, and is characterized by uniformity, strength and resistance to caving, compact structure, and low permeability. The 4.27 m thick immediate floor is dominated by mudstone or aluminous mudstone with dense structure and good watertightness, is the main aquifuge protecting the No. 15 seam from water from the Ordovician limestone.

Acknowledgments

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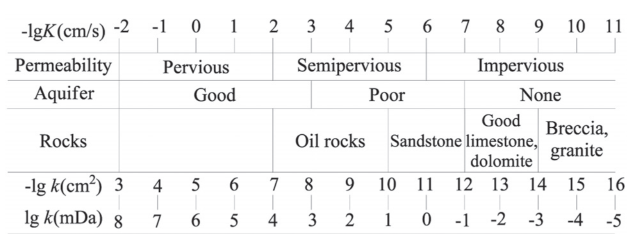

Figure 5—Typical values of hydraulic conductivity and permeability

Table IV

The conversion results of hydraulic conductivity *k* and permeability *K*

Specimens	k (10^{-15} cm²)	-lgK	-lgk	lgk
K_{2-1}	1.075–1228.338	6.936–9.994	11.911–14.968	-3.977–0.919
K_{2-2}	3.600–96.850	8.039–9.469	13.014–14.444	-3.452–2.022

Table III

Test parameters and results

Specimens	Size (mm)		Confining pressure (σ_3) (MPa)	Pore water pressure (MPa)	Osmotic pressure difference (MPa)	Peak stress (σ_1-σ_3) (MPa)	Peak strain (mm/mm)	Permeability (k) (10^{-06} Da) Hydraulic Conductivity (K) (10^{-10} cm/s)
	Diameter	Height						
K_{2-1}	49.4	69.8	5	4.8	1.5	174.4	0.0052	0.1055–120.5 1.014–1159
K_{2-2}	53.6	82.1	5	4.8	1.5	146.2	0.0076	0.3532–9.501 3.395–91.33

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