Study On Theory and Technology of Coordinated Mining of Coal and Associated Mineral Resources

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ABSTRACT

The coexisting and associated minerals of coal measures, overlapping with coal seams, have great differences in occurrences and mining methods. The rock stratum movement and fluid migration caused by the mining of each mineral affect each other's normal mining operations. Focusing on the coexisting and associated strategic metal minerals of coal measures, especially the typical bauxite and sandstone-type uranium deposit of coal measures, this study analyzes the interaction between longwall coal mining and room and pillar bauxite mining as well as that between longwall coal mining and in-situ leaching uranium mining. Also, by sorting out the common problems existing in the mining of the coexisting and associated minerals of coal measures, the concept of zoning and staggered coordinated mining of coal and its coexisting and associated minerals is clarified, and a complete set of coordinated mining modes of coordination, collaboration and co-mining is put forward. According to the characteristics of large differences in occurrences and mining methods of minerals of coal measures, this paper puts forward the coordinated mining mode of underground-underground mining, underground-drilling mining, underground co-mining and open-pit co-mining, which can ensure the universality of coordinated mining methods and improve the recovery ratio of coal and its coexisting and associated minerals of coal measures.

KEYWORDS

coal measures, coexisting and associated minerals, zoning and staggered, coordinated mining, mining mode

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1. INTRODUCTION

There are many kinds of coexisting and associated minerals in coal measures with rich reserves(Dai et al., 2020; National Bureau of Statistics of China, 2020; Ministry of Natural Resources, PRC, 2020; Dai et al., 2014), and the value of some minerals is much higher than that of coal itself (Table 1) (Wang et al., 2016; Wen et al., 2020; Ning et al., 2019; Ning et al., 2017; Li et al., 2014; Zhao et al., 2017; Qiao et al., 2016; Fang et al., 2018; Wang et al., 2010). For example, more than 50% of China's proven bauxite reserves in 2019 were coexisting bauxite of coal measures, and by the end of 2015, more than 60% of China's total proven uranium resources were coexisting sandstone-type uranium deposits of coal measures.

At present, the study of coordinated mining methods and modes of coal and its coexisting and associated minerals is still in preliminary exploration. Most mines still exploit single resources mainly because there is no mature and complete theory and technology system for coordinated mining of coal and its coexisting and associated minerals (Huang et al., 2019; Zhou, 2018; Yuan, 2019; Yuan et al., 2017). In Yili Basin and Ordos Basin, for example, the co-existence of various mineral resources is widespread. The coal and uranium reserves rank first in China's predicted resource reserves, and comprehensive exploration of "uranium and coal exploration" has been realized. However, the development of mineral resources is still dominated by single mineral species or a single industry, such as coal, uranium, oil and gas, etc. Due to the different exploration and utilization modes of mineral resources and the different requirements for hydrogeological conditions, it is easy to cause problems such as the mutual influence of mineral development, waste of resources, environmental pollution and hidden safety problems in the mining process. Therefore, while making full use of resources and protecting the environment, how to realize the coordinated and orderly development of coexisting and associated minerals to avoid disadvantages is widely noticed at present.

The influence of rock strata movement caused by coal mining on borehole stability of oil and gas wells was preliminarily explored (Liang, 2015). In terms of time sequence, mining mode and feasibility of coal-bauxite underground combined mining, four mining modes were put forward, i.e., mining coal seam firstly and then bauxite layer, mining bauxite layer firstly and then coal seam, alternate mining of coal seam and bauxite, and stratification inducement synergetic mining of coal seam and bauxite layer. Combined with the actual engineering geological conditions, the advantages, disadvantages and feasibility of the four mining modes are compared and analyzed (Wang et al., 2020). In terms of the theory and technology of open-pit co-mining of coal and coexisting bauxite, according to the characteristics of surface mining the multi-resources, the rules and method of the boundary demarcation of surface mine with multi-resources were put forward. The characteristics and main influencing factors of the balanced mining of coal and coexisting bauxite were analyzed, and the reasonable and economical exploitation resources and recovery resources of coal and bauxite are presented (Gao, 2017).

The coexisting and associated minerals of coal measures, overlapping with coal seams, have great differences in occurrences and mining methods. The rock stratum movement and fluid migration caused by the mining of each mineral affect each other’s normal mining operations. At present, traditional coal mines only exploit coal, and the other minerals associated with coal measures are given little consideration, leading to the waste of resources. It is urgent to overcome the bottleneck of coordinated mining technology of coal and its coexisting and associated minerals and establish a complete set of methods and modes for coordinated mining.

Based on the previous research (Huang et al., 2016; Huang et al., 2022), this paper analyzes the common problems existing in the mining of typical coexisting and associated minerals of coal measures in detail, and expounds on the concept of zoning and staggered coordinated mining. A complete set of coordinated mining

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modes of coordination, collaboration, and co-mining are proposed to ensure the universality of coordinated mining technology and improve the recovery ratio of coal and its coexisting and associated minerals of coal measures.

Table 1 - Types and reserves of part of coexisting and associated minerals in coal measures of China

Mineral species	Reserves
Bauxite	In 2019, China's accumulative identified resource reserves of bauxite were **5.47 billion tons**, among which the reserves of coal measures associated bauxite were about 2.94 billion tons, accounting for more than **50%** of the total reserves of bauxite in China, mainly distributed in Shanxi, Henan and Guizhou province.
Uranium	By the end of 2015, China's total proved uranium resources were about 286,000 tons, among which the reserves of coal measures associated sandstone-type uranium were about **191,000** tons, accounting for more than **60%** of the country's total reserves, mainly distributed in the top ten coal-accumulating basins in north China, such as Yili Basin, Ordos Basin, Erlian Basin and Qaidam Basin.
Germanium	The estimated reserves of germanium resources in China are about 9,119 tons, of which **7,519 tons** are associated with coal measures, accounting for more than **80%** of the total reserves in China, mainly distributed in Lincang, Yunnan Province, Shengli coalfield and Yimin coalfield in Inner Mongolia.
Gallium	The estimated reserves of gallium resources in China are about 330,000 tons, among which the reserves of gallium resources associated with coal measures are about **233,400 tons**, accounting for more than **60%** of the total reserves in China, mainly distributed in Inner Mongolia Junge coalfield, Daqingshan coalfield and so on.
Niobium	The proved reserves of niobium in China's coal measures are **196,400 tons**.
Rare Earth Element	REO reserves in the Junggar coalfield could reach **5 million tons**.
Zirconium	Yunnan Xuanwei (cattle farm-ancient mining area) zirconium reserves up to **1.58 million tons**.
Lithium	The amount of associated lithium resources in China's coal measures is up to **1.13 million tons**, which is mainly distributed in Inner Mongolia, Pingshuo, Shanxi and so on.
Beryllium	The beryllium resource of Dazhai mining area in Lincang, Yunnan Province is **224 tons**.
Vanadium	The utilization of vanadium in coal in China is mainly extracted from stone coal, in which the reserves of V_2O_5 are **118 Mt**, accounting for **87%** of the country's total reserves.

2. PROBLEMS IN MINING COAL AND ITS COEXISTING AND ASSOCIATED MINERALS OF COAL MEASURES

Coal-bauxite and coal-uranium are typical coexisting minerals of coal measures. Coal, bauxite and uranium are mined by longwall, chamber and column and drilling methods respectively. The typical mining methods

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for coal, bauxite and uranium are long-wall mining, room and pillar mining and drilling mining respectively. Aiming at all the co-existed and associated strategic metal minerals of coal measures, this study focus on the representative bauxite and sandstone-type uranium deposit of coal measures to analyze the common problems existing in the mining of the coexisting and associated minerals of coal measures.

2.1 Interaction between Longwall Coal Mining and Room and Pillar Bauxite Mining in Coal Measures

For coal and coexisting bauxite mining with upper coal and lower bauxite occurrence characteristics, if the lower bauxite is mined first, on the one hand, the roof of the goaf would be unstable and falls after the bauxite is mined-out, causing the upper coal seam to break and step, destroying the continuity of the coal seam and affecting normal mining of the coal seam. On the other hand, the mining of lower bauxite causes mining-induced fractures in the roof to develop and expand to the upper coal seam, resulting in toxic and harmful gases such as CH_4 and H_2S in the coal seam entering the bauxite stope along the mining-induced fractures, which affects the safe mining of bauxite.

If the upper coal seam is mined first and then the lower bauxite is mined, on the one hand, during the mining of the upper coal seam, due to the influence of the mining disturbance of the coal seam, the rock fracture of the coal seam floor develops, and the toxic and harmful gases such as CH_4 and H_2S and the water in the goaf enter the mining-induced fracture of the floor. When the lower bauxite is mined, the roof cracks of the bauxite stope expand upward and link up with the mining-induced fractures of the upper coal seam floor. Harmful gases such as CH_4 and H_2S and water in the coal seam goaf will penetrate into the bauxite stope along the mining-induced fractures, affecting the safety production of bauxite. On the other hand, the upper coal seam mining causes the stress concentration of the coal seam floor (bauxite roof), and the lower bauxite mining causes secondary disturbance to the overlying strata. The superposition of strata movement in multi-mineral mining causes the instability of the lower bauxite pillar, which leads to the instability of the bauxite roof and seriously threatens the safety of bauxite mining.

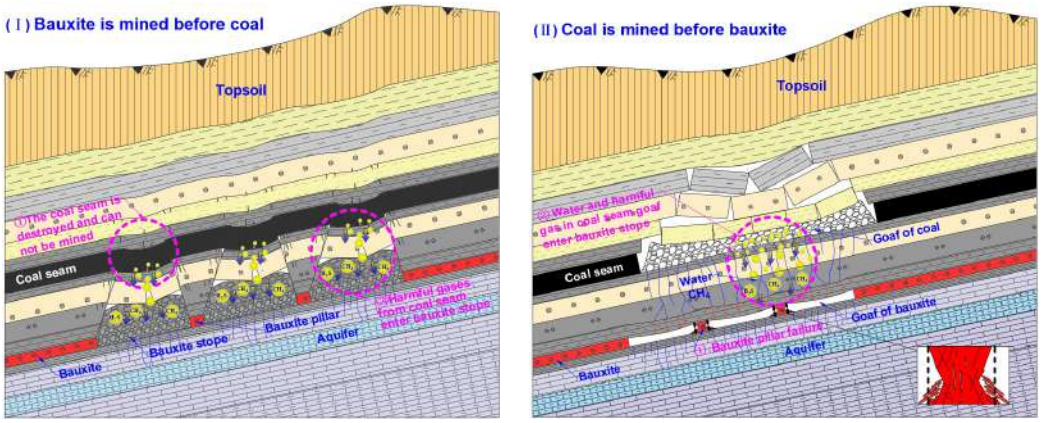

Figure 1 - Problems in coal-bauxite mining (Huang et al., 2022)

2.2 Interaction between Longwall Coal Mining and In-Situ Leaching Uranium Mining in Coal Measures

Sandstone-type uranium deposit occurs in confined aquifers, and the roof and floor are impermeable strata. A critical water level is required to ensure the normal operation of in-situ uranium leaching. For coal and coexisting uranium mining with the occurrence characteristics of upper uranium and lower coal, after the coal mining near the uranium mine, the mining-induced fractures in the roof of coal seam develop and expand, which are connected with the ore-bearing aquifer of the uranium mine, causing the water level to drop. When

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the impermeable layer is broken under the influence of mining, the water level will drop sharply, which leads to the failure of in-situ leaching of uranium deposit. At the same time, nuclear and radon pollutants from uranium deposit migrate to the coal mine, affecting the safety of coal mine production. In addition, the rock strata movement caused by coal mining will lead to the deformation of the pumping fluid well and the monitoring well wall, and even the shear rupture of the shaft wall, which will affect the stability of the shaft wall.

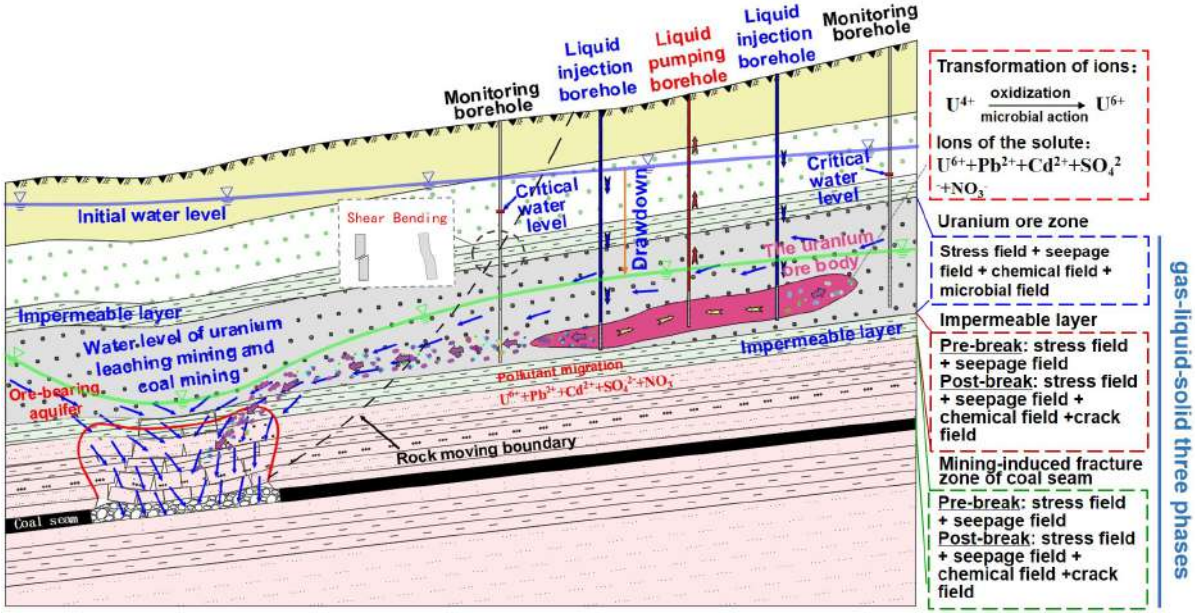

Figure 2 - Problems in coal-uranium mining (Huang et al., 2022)

3. THE CONCEPT OF ZONING AND STAGGERED COORDINATED MINING OF COORDINATION, COLLABORATION AND CO-MINING OF COAL AND ITS COEXISTING AND ASSOCIATED MINERALS

Aiming at the drawbacks that the traditional mining method can not solve the contradiction of mining coal and its coexisting and associated minerals, this paper puts forward the zoning and staggered coordinated mining method of coordination, collaboration and co-mining. This method takes "zoning and stagger" as the core idea, and takes "zoning, timing staggered, urgently needed first extraction, comprehensive utilization, reasonable avoidance" as the design principle. By overall consideration of the layout, mining time, scale and structure of resources, coordinate the mining relationship among various minerals, and then extract different minerals at different times or in different zones, solving the contradiction between coal and its coexisting and associated minerals effectively, which reduces the waste of resources greatly and enables coordinated mining.

3.1 Principle of Zoning and Staggered Coordinated Mining

According to the occurrence characteristics, distribution range and mining methods of coal and coexisting minerals, a comprehensive analysis is made from the following aspects: the size of the distribution area, occurrence layer and the relative spatial relationship between coal and coexisting minerals. Next, the mining methods of coal and coexisting mineral are determined respectively, and the mining technical requirements and adverse effects of the two mining methods are analyzed. Further, according to the distribution region

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and relative spatial relationship between coal and coexisting minerals, it is necessary to analyze which regions of minerals will be adversely affected by the exploitation of another mineral, leading to the destruction of mining technical conditions of minerals in this region and the failure of normal mining. Finally, the contradiction points of mining coal and coexisting minerals are summarized.

In view of the contradiction of mining coal and coexisting minerals, the mining area is rationally zoned and mined at different times according to the design principles of zoning, timing staggered, urgently needed first extraction, comprehensive utilization and reasonable avoidance. The layout, timing, scale and structure of resource exploitation should be fully considered when the mineral resources are divided into different areas. The strategic demand, occurrence characteristic, exploitation influence and economic value of resources should be considered comprehensively when determining the exploitation time sequence of resources. The core judgment basis of the reasonable regional division and time sequence is whether the design can solve or avoid the contradiction of mining coal and coexisting minerals, and achieve the purpose of coordinated mining.

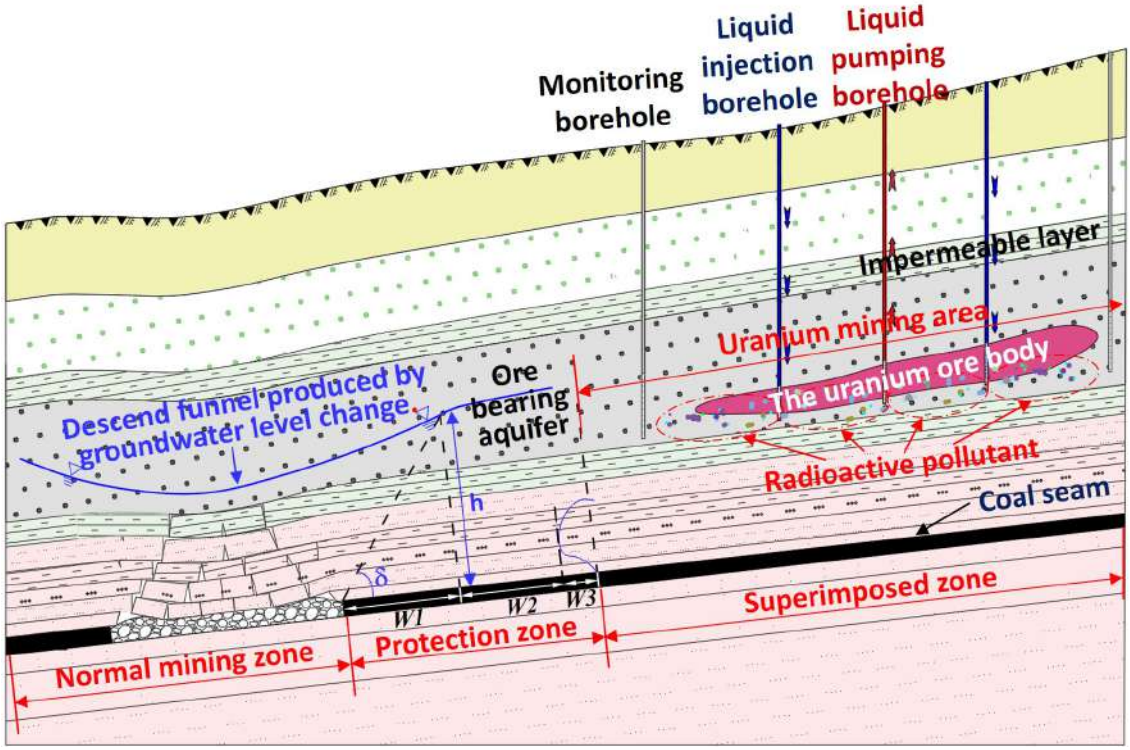

Figure 3 - Schematic diagram of zoning and staggered coordinated mining of coal mining and coexisting mineral drilling

Based on the above analysis, the coal and coexisting mineral resources area is divided into three parts: superimposed area, protected area and normal mining area. The superposition area is the mineral occurrence area where the coal seam and the coexisting mineral space are overlaid. The protected area is the area that is not planned to be mined. As a buffer between the superimposed area and normal mining area, this area can effectively reduce the impact of coal seam and coexisting mineral mining on each other. Normal mining area is the area outside the protected area. Because of the buffer of the protected area, normal mining activities can be carried out in this area. The size of the protected area is determined according to the lateral boundary of the water-conducting fracture zone in the overlying strata on the mining working face. As an

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intermediate buffer area between the superimposed area and normal mining area, the protected area is affected by the rock strata movement in normal mining area on one side and the mining activity in the superimposed area on the other side. Therefore, the scope of the protected area should be larger than the sum of the influence areas of normal mining area and the superimposed area, to prevent the interpenetration of the fractures in normal mining area and the superimposed area, and the occurrence of mine water inrush accidents and the migration and diffusion of toxic and harmful gases.

In view of the divided regional mineral resources, reasonable mining method and technology are selected for orderly mining. Theoretically, minerals in normal mining area should be mined first, and then those in the superimposed area. Due to the superposition of coal and coexisting minerals in the superposition area, it is necessary to comprehensively consider the strategic attributes, economic value, demand priority and other conditions of mineral resources, and finally determine whether to give priority to mining the upper or lower minerals. The minerals in the protected area are generally not mined, for more developed cracks, poorer structural stability of the minerals and surrounding rocks and greater mining difficulty, under the influence of long-term repeated mining disturbance in the overlapping area on both sides and normal mining area. If the mineral resources in the protected area are to be recovered, a comprehensive assessment of security, technology and economy is required before it can be carried out. According to the determined zoning and the mining sequence of each area, the superimposed distributed coal and coexisting minerals can be mined in an orderly manner.

3.2 A Complete Set of Coordinated Mining Modes of Coordination, Collaboration and Co-mining

Coordinated mining in a broad sense includes three modes: coordination, collaboration and co-mining. Among them, coordinated mining refers to avoiding adverse factors during mining, that is, taking measures to avoid the influence of rock strata movement caused by mining and ensuring the safe mining of coal and coexisting and associated minerals. Collaborative mining refers to the exploitation of coal and coexisting and associated minerals by the superposition of rock strata movement. That is, utilizing the influence of rock strata activity, not only does not cause damage to mineral resources, but also has a positive effect on coal and coexisting and associated mineral mining. Co-mining refers to the exploitation of coal and coexisting and associated minerals using a shared production system.

(1) Coordinated mining

In coordinated mining, according to the principle of "zoning to avoid mutually adverse effects", the mineral occurrence area is divided into three parts: coal mining area, coexisting minerals mining area and protection area, with overall consideration of the layout, timing and scale of resource exploitation. As a buffer area between the coal mining area and coexisting mineral mining area, the minerals in the protected area are not mined to avoid rock strata movement affecting normal mining. The minerals in the coal mining area and coexisting mineral mining area are mined in the direction diverging from the protected area.

(2) Collaborative mining

In collaborative mining, according to the principle of "staggered exploitation time sequence and utilization of rock strata movement", the mining area is divided into "priority mining area" and "lag mining area", and the reasonable mining method and layout are determined for mining. By utilizing the rock strata movement caused by mining in "priority mining area", the mining of minerals in "lag mining area" will be more efficient and safe, achieving the collaborative mining of coal and coexisting and associated minerals.

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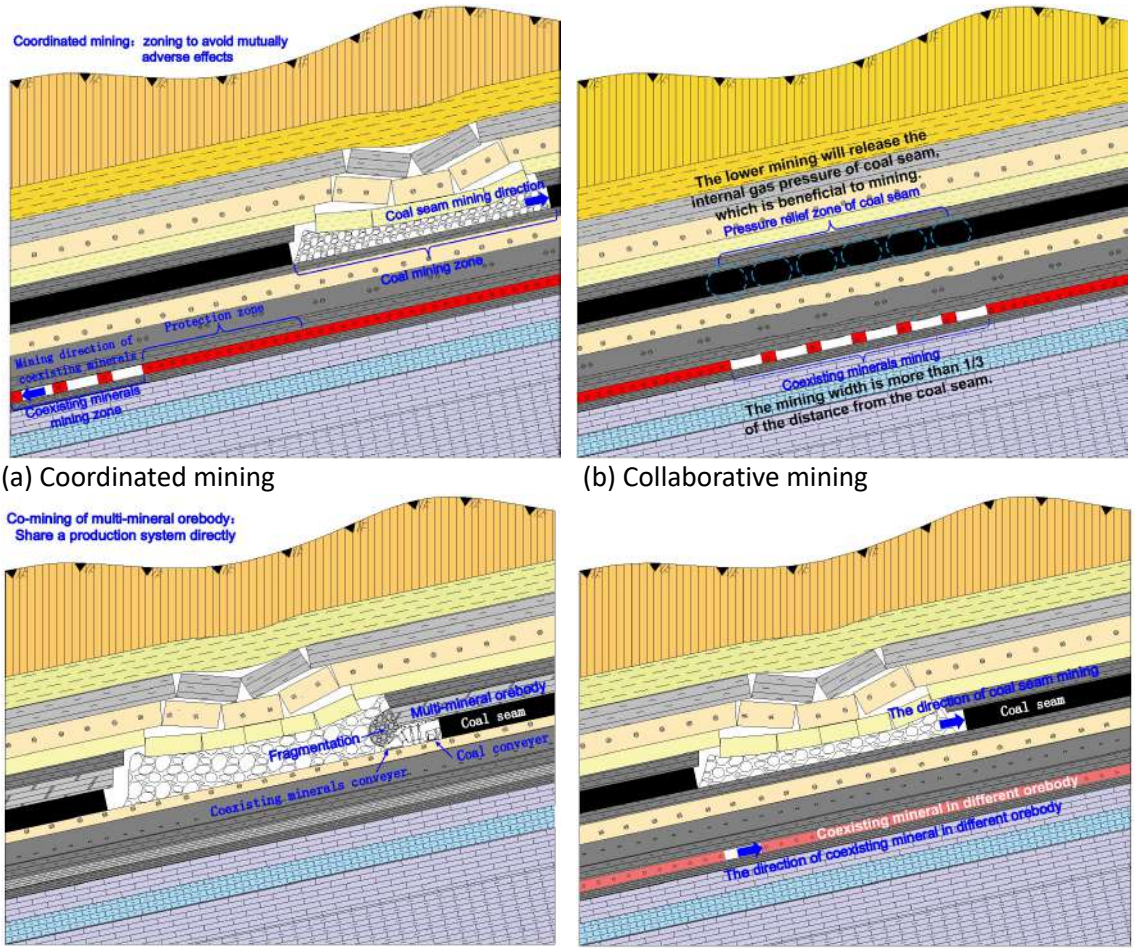
(3) Co-mining

The co-mining mode includes co-mining of multi-mineral orebody and co-mining of coexisting mineral in different orebody. For multi-mineral orebody, coal and coexisting minerals can be mined together in a common production system. In view of the coexisting mineral in different orebody, it is necessary to develop and extend the depth, connect the two sets of production systems of coal and coexisting minerals, and share the development of mining tunnels and transportation systems to extract the minerals.



(a) Coordinated mining (b) Collaborative mining

(c) Co-mining

Figure 4 - Principle of coordination, collaboration and co-mining of coal and coexisting and associated minerals (Huang et al., 2022)

4. COORDINATED DEVELOPMENT MODE OF COAL AND ITS COEXISTING AND ASSOCIATED MINERALS

The exploitation mode of coal and coexisting and associated minerals is the link between coordinated mining methods and field engineering demonstration. According to the characteristics of large differences in occurrences and mining methods of minerals of coal measures, this paper puts forward the coordinated mining mode of underground-underground mining, underground-drilling mining, underground co-mining and open-pit co-mining, which can ensure the universality of coordinated mining methods and improve the recovery ratio of coal and its coexisting and associated minerals.

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4.1 The Coordinated Exploitation Mode of Underground-Underground Mining

The coordinated exploitation mode of underground-underground mining means that both coal and coexisting solid minerals adopt underground mining, and the two production systems are independent of each other. The overall mining planning of minerals shall be coordinated before mining, and the whole mining process of the two production systems shall be monitored in the whole region to avoid the negative influence of mining activities. This mode is suitable for coal and coexisting solid mineral combination with the deep occurrence and belonging to different enterprises respectively. If the deep mineral deposits are mined by open pit, the stripping ratio will far exceed the economically reasonable stripping ratio, which is not technically and economically rational.

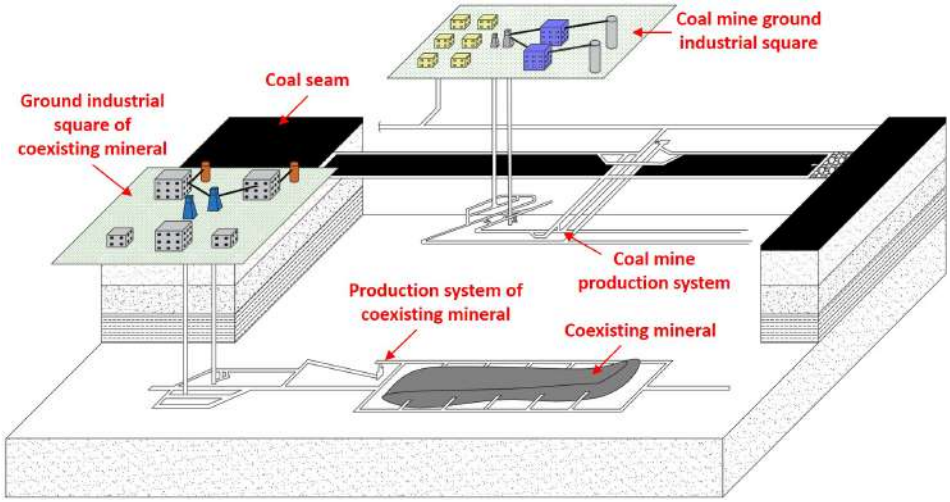

Figure 5 - The coordinated exploitation mode of underground-underground mining (Huang et al., 2022)

4.2 The Coordinated Exploitation Mode of Underground-Drilling Mining

The coordinated exploitation mode of underground-drilling mining refers to that coal and coexisting mineral mining methods are underground mining and drilling respectively, the two production systems being independent of each other. The overall mining planning of minerals shall be coordinated before mining, and the whole mining process of the two production systems shall be monitored in the whole region to avoid the negative influence of mining activities. This mode is applicable to the combination of coal and coexisting fluid minerals or solid minerals mined by fluidization. In order to reduce the negative impact of exploitation, the following coordinated development measures should be taken: strengthen the shear resistance of the wellbore, and reduce the range and intensity of rock strata movement near the wellbore by adjusting the layout of coal mining.

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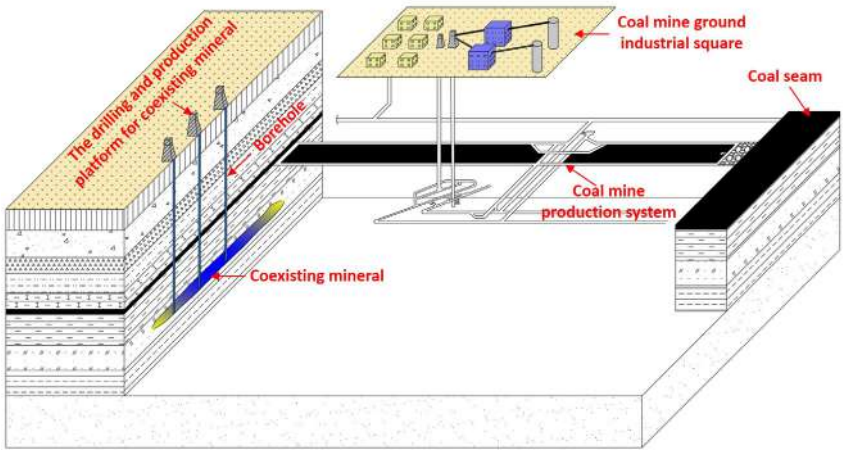

Figure 6 – The coordinated exploitation mode of underground-drilling mining (Huang et al., 2022)

4.3 The Coordinated Exploitation Mode of Underground Co-mining

For deep coal and coexisting solid minerals, the stripping ratio of open-pit mining is far more than the economically reasonable stripping ratio, which is not reasonable in technology and economy. At the same time, if coal and coexisting solid minerals are mined by the same enterprise, the coordinated exploitation

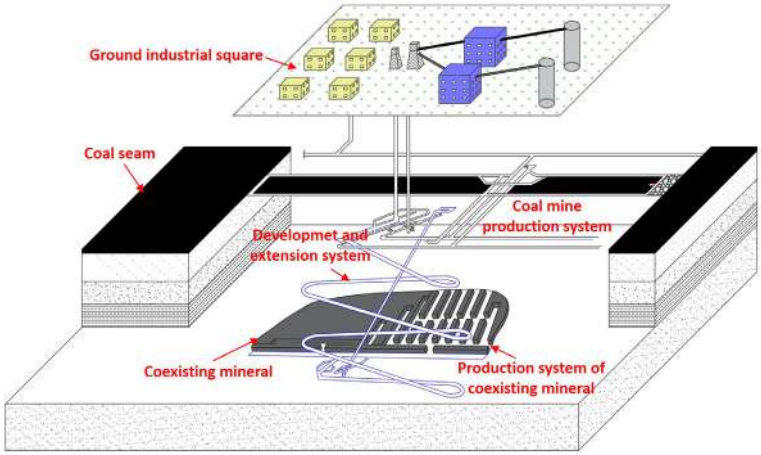

Figure 7 - The coordinated exploitation mode of underground co-mining (Huang et al., 2022)

mode of underground co-mining can be selected. In this mode, both coal and coexisting solid mineral adopt underground mining, but the common part of the production system of coal mining and coexisting solid mineral mining can be shared, and there is no need to repeatedly build two completely independent production systems, which can greatly reduce the volume of engineering construction. However, this mode puts forward higher requirements for mining enterprises, and it is necessary to coordinate the mining, transportation and safety management of the two kinds of minerals under the same production system.

The mining method and development method are selected according to the comprehensive analysis of the geological conditions. The layout of the working face should take into account the mutual impact between

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the mining of the two minerals. For coal and coexisting minerals, it is necessary to design two separate transport systems, which can not be mixed to facilitate surface sorting. The coordination degree of the two transport systems should be reasonably planned so that their transport capacity corresponds to their respective production capacity (especially the skip lifting system of the vertical shaft).

4.4 The Coordinated Exploitation Mode of Open-pit Co-mining

For shallow buried coal and coexisting solid minerals, the stripping ratio of open-pit mining is less than the economically reasonable stripping ratio. In open-pit mining, large-scale mining and transportation equipment can be used, which has high efficiency, low cost, high safety and high ore recovery ratio. Based on the rationality of the technology and economy, the open-pit mining method is adopted for both coal and coexisting solid minerals. Therefore, the coordinated development mode of open-pit co-mining can be selected under this condition. Before mining, it is necessary to delineate the mining boundary of coal and coexisting minerals and determine the main mining resources and mine production capacity. According to the occurrence characteristics and mechanical properties of minerals, the mining technology is determined, and reasonable mining procedures and transportation systems are designed to ensure the production stability of coal and coexisting minerals.

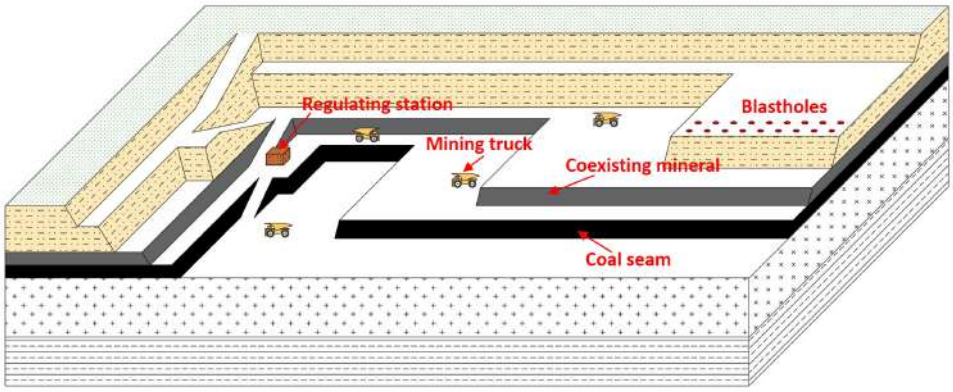

Figure 8 - The coordinated exploitation mode of open-pit co-mining (Huang et al., 2022)

5 CONCLUSIONS

(1) The interaction between longwall coal mining and room and pillar bauxite mining is analyzed. When bauxite is mined first, the coal seam is destroyed and difficult to be mined, and the harmful gas from coal seam enters the bauxite stope. When the coal is mined first, the water and harmful gas in the goaf will enter the bauxite stope, and the bauxite roof will be more prone to instability for stress concentration.
(2) The interaction between longwall coal mining and in-situ leaching uranium mining in coal measures is analyzed. When the impermeable layer is broken under the influence of mining, the water level will drop sharply, which leads to the failure of in-situ leaching of uranium deposit. In addition, nuclear and radon pollutants from uranium deposit migrate to the coal mine, affecting the safety of coal mine production.
(3) The concept of zoning and staggered coordinated mining of coal and its coexisting and associated minerals is clarified. The coal and coexisting mineral resources area is divided into three parts: superimposed area, protected area and normal mining area. The layout, timing, scale and structure of resource exploitation should be fully considered when the mineral resources are divided into different areas. The strategic demand, occurrence characteristic, exploitation influence and economic value of

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resources should be considered comprehensively when determining the exploitation time sequence of resources.

(4) A complete set of coordinated mining modes of coordination, collaboration and co-mining is put forward. Coordinated mining refers to avoiding adverse factors during mining. Collaborative mining refers to taking advantage of the superposition of the rock strata movement during mining. Co-mining refers to the exploitation of coal and coexisting and associated minerals using a shared production system.

(5) According to the characteristics of large differences in occurrences and mining methods of minerals of coal measures, this research puts forward the coordinated mining mode of underground-underground mining, underground-drilling mining, underground co-mining and open-pit co-mining, which can ensure the universality of coordinated mining methods and improve the recovery ratio of coal and its coexisting and associated minerals.

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