

Identification of Hazard-Source Indicators for Coal Spontaneous Combustion in Deep Mine Goafs

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Abstract

To improve the proactive prevention and control of coal spontaneous-combustion disasters in the goafs of deep coal mines, this study identifies the factors associated with hazard-source recognition for coal spontaneous combustion in the goaf of a coal mine in Hebi, China. The mine is characterized by coal-seam explosibility and spontaneous-combustion proneness, large quantities of residual coal under fully mechanized top-coal caving, a complex air-leakage field, and concealed fire sources that are difficult to detect in a timely manner. On the basis of systems engineering theory and accident-causation theory, literature analysis, field investigation, and expert evaluation were integrated to conduct hierarchical identification of hazard sources related to goaf coal spontaneous combustion. A risk-evaluation indicator system was then established from four dimensions: human factors, equipment factors, environmental factors, and management factors. The results indicate that goaf coal spontaneous combustion is not governed by a single factor; rather, it is a dynamic disaster process driven by the coupled effects of residual-coal oxidation and heat accumulation, air leakage and oxygen supply, production organization, equipment reliability, and management execution. Among the identified indicators, the accuracy of early hazard recognition, reliability of standby power supply and emergency equipment, matching degree between longwall face advance rate and the spontaneous-combustion period, and closed-loop rate of hazard investigation and rectification exert critical influences on risk evolution. The findings provide theoretical support for precise prevention and control of goaf coal spontaneous-combustion risk in the studied mine and offer a reference for fire-prevention and fire-extinguishing management in similar deep, fully mechanized top-coal-caving mines.

Keywords

Coal Mine Safety; Goaf; Coal Spontaneous Combustion; Hazard-Source Identification

1. Introduction

Coal is a fundamental energy source within China's energy-security system and has

long occupied an important position in the structure of primary energy production and consumption. Owing to the resource endowment of abundant coal, limited oil, and scarce natural gas, coal not only serves as the main support for power supply but also provides essential raw material for basic industries such as iron and steel, building materials, and chemical production^[1]. As coal-resource extraction extends to greater depths, the mining environment becomes increasingly complex, and mine disasters exhibit multi-source coupling, concealed evolution, and abrupt transformation. As one of the major disasters in coal mines, coal spontaneous combustion in goafs is characterized by weak early symptoms, concealed spatial occurrence, high treatment difficulty, and severe secondary-disaster consequences. If not controlled promptly, it may induce gas explosions, roadway sealing, longwall face shutdowns, and even mass-casualty accidents.

The state has attached considerable importance to mine fire prevention and extinguishing. The newly revised Coal Mine Safety Regulations strengthened technical standards for spontaneous-combustion monitoring as well as grouting and nitrogen-injection measures^[2]. The Detailed Rules for Coal Mine Fire Prevention and Extinguishing systematically stipulate whole-process requirements and implement the principle of prediction and forecasting^[3].

In recent years, fully mechanized top-coal caving has been widely applied in thick-seam mining, improving resource recovery and mine production capacity. However, this method also increases the amount of residual coal in the goaf^[4]. After residual coal is broken and accumulated in the goaf, its specific surface area increases, making oxygen adsorption and low-temperature oxidation reactions more likely to occur. When air-leakage pathways, heat-storage conditions, and residence time simultaneously satisfy the conditions for spontaneous combustion, a positive feedback process of oxygen supply, oxidation, heat release, heat accumulation, and temperature rise may be formed. Under deep-mining conditions in particular, elevated geothermal temperature, increased in-situ stress, the development of surrounding-rock fractures, and the increasing complexity of ventilation networks further intensify the uncertainty of goaf coal spontaneous combustion. Traditional fire-prevention and fire-extinguishing management modes that rely mainly on empirical judgement, static checklists, and monitoring of individual indicators can no longer satisfy the requirements for precise identification, dynamic evaluation, and graded treatment under complex operating conditions.

During deep fully mechanized top-coal-caving operations, the studied coal mine in Hebi faces problems such as uneven distribution of residual coal, development of mining-induced fractures, complex air-leakage channels, and growing pressure on fire-prevention and fire-extinguishing management. Although the mine has established a certain monitoring and fire-control system, there remains room for improvement in the systematic identification of hazard sources and the precision of

control measures. Therefore, this paper takes the risk of goaf coal spontaneous combustion in the mine as the research object and investigates hazard-source identification and prevention-control strategies. The aim is to promote the transformation of goaf coal spontaneous-combustion risk management from experience-based management to scientific, systematic, and dynamic control.

2. Engineering Background and Problem Analysis

2.1. Risk Characteristics of Coal Spontaneous Combustion in the Mine Goaf

The coal seam of the studied mine exhibits typical coal spontaneous-combustion risk characteristics in terms of spontaneous-combustion tendency, mining intensity, ventilation conditions, and goaf spatial structure. First, the coal seam itself provides the material basis for spontaneous combustion. After mining-induced crushing, the coal body forms a large quantity of fine residual coal; the pore structure and fracture network become more developed, and oxygen diffusion and adsorption channels increase, providing sufficient contact area for low-temperature oxidation. Second, during fully mechanized top-coal caving, spatial differences exist in top-coal caving rate, recovery rate, and the caving state of the goaf, and local residual-coal enrichment zones readily become heat-accumulation areas. Third, the goaf air-leakage field is jointly controlled by the ventilation mode of the working face, the quality of stoppings, the influence of mining in adjacent working faces, and the development degree of surface or roadway fractures. Local areas may therefore form hazardous air-leakage intensity ranges that can supply oxygen while being unfavorable for heat dissipation. Finally, with increasing mining depth, the rise in original rock stress and geothermal temperature intensifies surrounding-rock deformation and failure, causing air-leakage pathways and heat-storage conditions in the goaf to change dynamically.

From the perspective of the evolution mechanism of coal spontaneous combustion, four basic conditions are required for goaf coal spontaneous combustion: residual coal, oxygen, a heat-storage environment, and sufficient oxidation time. Residual coal is the material basis of the reaction; air leakage is the oxygen-supply source; the compaction degree of the goaf and the heat-conduction conditions determine whether heat can accumulate; and the advance rate of the working face affects the residence time of residual coal within the oxidation zone. When the working-face advance rate does not match the natural spontaneous-combustion period of the coal seam, or when the oxidation zone expands and remains for a long time in residual-coal enrichment areas, the spontaneous-combustion risk increases significantly. Therefore, risk evaluation of goaf coal spontaneous combustion should not rely solely on a single monitoring indicator such as CO concentration or temperature. Instead, it should comprehensively consider coal-oxygen interaction, air leakage and oxygen supply, mining-induced fractures, equipment support, and

management execution.

2.2. Deficiencies in Existing Identification and Evaluation Practices

Combined with current fire-prevention and fire-extinguishing management practices, the identification of hazard sources for goaf coal spontaneous combustion mainly has the following deficiencies.

First, hazard-source identification tends to be static and fragmented. Existing identification work is mostly based on regulatory provisions, enterprise-standard checklists, and safety inspection forms. It can identify explicit risk factors such as increased CO concentration, abnormal temperature, insufficient grouting, and slow advance rate. However, insufficient attention is paid to concealed disaster-causing factors under deep-mining conditions, such as dynamic fracture development induced by stress evolution, airflow disturbance within complex ventilation networks, and changes in the microscopic pore structure of coal. Because these factors are not easily observed in routine inspections, failure to incorporate them into the identification system may create risk blind spots.

Second, risk evaluation is strongly subjective and lacks stable quantitative support. On-site risk-level judgement usually depends on expert experience and managers' intuitive understanding of monitoring-data changes. This approach has the advantages of rapid response and simple operation. However, different personnel may perceive the importance of the same risk factor differently, and weight allocation is easily affected by individual experience, resulting in insufficient comparability and objectivity of evaluation results. Especially when multiple factors change simultaneously, purely experience-based judgement is inadequate for accurately revealing the amplification effects generated by risk coupling.

Third, early warning and treatment measures are often delayed. Goaf coal spontaneous-combustion risk evolves dynamically, and the risk level may change rapidly with variations in advance rate, barometric pressure, stopping leakage, grouting quality, and adjacent mining influence. If risk-evaluation results cannot be promptly converted into graded warnings and differentiated treatment measures, fire-prevention and fire-extinguishing work may easily fall into either one-size-fits-all full-coverage treatment or passive response. Excessive grouting or nitrogen injection not only increases production cost but may also affect the normal advance of the working face, whereas insufficient treatment may miss the window for early intervention.

Fourth, management closure and cross-departmental collaboration still require strengthening. Prevention and control of goaf coal spontaneous combustion involve several professional systems, including ventilation, geological surveying, mining, electromechanical engineering, and safety supervision. If monitoring data are not shared in a timely manner, hidden-hazard rectification responsibilities are unclear, or engineering acceptance becomes a mere formality, the practical effectiveness of fire-prevention and fire-extinguishing technical measures will be weakened.

Therefore, constructing an integrated evaluation system that includes personnel behavior, equipment status, environmental conditions, and management capability is essential for improving the precision of spontaneous-combustion risk control.

3. Theory and Methodology for Hazard-Source Identification

3.1. Classification Logic of Hazard Sources

According to accident-causation theory, hazard sources for goaf coal spontaneous combustion can be divided into three categories. The first category consists of the material and energy basis of an accident, mainly including residual coal in the goaf, oxygen, and the potential for oxidative heat release. Such hazard sources exist objectively and are difficult to eliminate completely, but they can be controlled by reducing residual coal, isolating oxygen, and weakening heat-storage conditions. The second category consists of direct triggers that lead to loss of control over first-category hazard sources, mainly including unsafe human behavior, equipment failure, abnormal air leakage, unreasonable advance rate, and stopping leakage. The third category consists of deep-seated management deficiencies, such as an incomplete institutional system, inadequate responsibility implementation, insufficient training, non-closed-loop hazard treatment, and a weakened safety culture. The three types of hazard sources show an evident chain relationship: management deficiencies induce unsafe human behavior and unsafe equipment or facility states, which then cause loss of control over the conditions of residual coal, oxygen, and heat accumulation, ultimately leading to a spontaneous-combustion accident.

In risk prevention and control of coal spontaneous combustion, first-category hazard sources are the treatment objects, second-category hazard sources are the control priorities, and third-category hazard sources are the root causes for long-term governance. If attention is limited to outcome-oriented indicators such as CO concentration and temperature, countermeasures are often implemented only after the risk has become explicit. In contrast, identifying second- and third-category hazard sources from the four dimensions of human factors, equipment factors, environmental factors, and management factors enables intervention at the front end of the accident chain and promotes the transition from post-accident treatment to risk-prevention-oriented precontrol.

3.2. Combined Technical Route for Identification

Considering the complexity of influencing factors, diversity of data sources, and significant mechanism coupling associated with goaf coal spontaneous-combustion risk, this study constructs a combined identification route comprising literature analysis, field investigation, and factor screening.

First, through literature analysis and review of regulations and standards, the occurrence conditions, key indicators, and compliance requirements for goaf coal

spontaneous combustion and fire prevention are clarified, and an initial list of hazard sources is formed. This stage focuses on coal-oxygen interaction theory, the three-zone distribution theory, the evolution law of air-leakage flow fields, and the technical requirements of fire-prevention and fire-extinguishing engineering, thereby ensuring that indicator setting has both theoretical and regulatory foundations.

Second, field investigations are conducted. Through underground site inspection, personnel interviews, review of tube-bundle monitoring data, analysis of temperature-measurement records, and verification of fire-prevention and fire-extinguishing engineering documents, theoretical indicators are matched with actual on-site hazards. For factors that do not exist on site or have remained stably controlled for a long period, their weights can be appropriately reduced. Conversely, geological structures, ventilation conditions, equipment-operation issues, and management loopholes specific to the mine should be added to the indicator system. Finally, the initial hazard sources are structurally screened. The goaf system is decomposed into four subsystems: personnel, equipment, environment, and management^[5]. Each hazard source is assessed in terms of compliance, harmfulness, and evaluability. Indicators that are obviously irrelevant or for which data are difficult to obtain are removed, resulting in a screened indicator pool.

4. Identification of Hazard-Source Indicators for Goaf Coal Spontaneous Combustion

4.1. Human-Factor Indicators

Human factors mainly reflect the influence of individual operating behavior, risk-identification capability, and emergency-response capability on the effectiveness of coal spontaneous-combustion prevention and control. Four core indicators can be established for human factors in goaf coal spontaneous combustion: implementation rate of fire-prevention and fire-extinguishing inspections, accuracy of early hazard recognition, safety psychological state, and proficiency in emergency-response operations, as shown in Table 1.

Table 1. Summary of human-factor hazard-source indicators.

No.	Indicator	Definition and description
1	Implementation of fire-prevention and fire-extinguishing inspections	Measures the proportion of substantive inspections conducted along prescribed routes and at prescribed frequencies for key facilities such as stoppings and pipelines, thereby preventing missed inspections and false inspections.
2	Accuracy of early hazard recognition	Represents the ability to accurately identify true early signs of spontaneous combustion, such as slight CO increases or abnormal Graham's coefficient values, from noisy and complex monitoring data.
3	Safety psychological state	Evaluates complacency, paralysis of thought, and risk-taking tendencies, and reveals deeper risks such as experience-based overconfidence formed under long-term accident-free conditions.

4	Proficiency in emergency-response operations	Assesses the standardization and rapidity with which emergency plans are implemented and determines whether the accident chain can be effectively cut off during the initial stage of a disaster.
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Among the human-factor indicators, the accuracy of early hazard recognition corresponds to the golden window for fire-prevention and fire-extinguishing work. Compared with hardware alone, personnel sensitivity to weak signs, such as minor anomalies in Graham's coefficient, directly determines whether hazards can be eliminated during the oxidation stage. If this indicator is omitted, minor hazards may readily evolve into major fire disasters.

4.2. Equipment-Factor Indicators

Equipment factors constitute the material support for monitoring, early warning, and treatment of goaf coal spontaneous-combustion risk. Unreliable equipment directly weakens early perception and engineering response capabilities. Combined with on-site conditions, equipment factors can be divided into seven indicators: integrity rate of CO/O₂/temperature sensors, unobstructed flow and sealing performance of grouting/nitrogen-injection pipelines, operating efficiency of nitrogen generators and grouting pumps, airtightness of firewalls or stoppings, response speed of intelligent early-warning systems, implementation rate of equipment maintenance plans, and reliability of standby power supply and emergency equipment, as shown in Table 2.

Table 2. Summary of equipment-factor hazard-source indicators.

No.	Indicator	Definition and description
1	Integrity rate of CO/O ₂ /temperature sensors	Reflects the online operating status and data accuracy of key underground monitoring devices, ensuring that changes in gas concentration and temperature in the goaf can be captured in real time and with fidelity.
2	Unobstructed flow and sealing performance of grouting/nitrogen-injection pipelines	Measures the physical condition of fire-control material delivery channels, requiring pipelines to be free from blockage and leakage and ensuring that terminal pressure satisfies delivery requirements.
3	Operating efficiency of nitrogen generators and grouting pumps	Assesses whether the actual output capacity of core fire-prevention and fire-extinguishing equipment, such as nitrogen purity, flow rate, and grouting pressure, meets design standards.
4	Airtightness of firewalls or stoppings	Evaluates the compactness and air-leakage resistance of sealing facilities and represents a key barrier for cutting off oxygen supply to the goaf.
5	Response speed of intelligent early-warning systems	Measures the response time from receiving abnormal data to issuing an alarm signal or even automatically linking control equipment.
6	Implementation rate of equipment maintenance plans	Quantifies the extent to which preventive maintenance is completed on time and with required quality, reflecting the standardization of full-life-cycle equipment management.
7	Reliability of standby power supply and emergency equipment	Evaluates the success rate and stability of standby power switching and emergency-equipment start-up when the main power-supply system fails or a sudden disaster occurs.

The reliability of standby power supply and emergency equipment ranks first among equipment factors in expert scoring because it directly determines system

resilience during a disaster. During the evolution of a goaf coal spontaneous-combustion accident, once the fire passes a critical point, it may readily cause power-grid short circuits or force the shutdown of the main ventilation system. If the standby power supply cannot switch instantaneously at that time, the monitoring system will become blind, and decision makers will lose their perception of the fire situation. If emergency fire-prevention and fire-extinguishing equipment cannot start, inertization or sealing cannot be implemented within the golden response period. For the studied mine, this indicator constitutes the last line of defense after the failure of all active defense measures, and its reliability directly determines whether an accident can be controlled at the incipient stage. It is therefore regarded as the most critical equipment-guarantee indicator.

4.3. Environmental-Factor Indicators

Environmental factors are the external conditions under which goaf coal spontaneous combustion occurs and develops, mainly including air leakage and oxygen supply, heat-storage space, mining influence, and production organization. This study sets five environmental indicators: goaf air-leakage velocity, width of the three zones and position of the oxidation zone, matching degree between working-face advance rate and the spontaneous-combustion period, influence of abutment pressure from adjacent working faces, and goaf water accumulation, as shown in Table 3.

Table 3. Summary of environmental-factor hazard-source indicators.

No.	Indicator	Definition and description
1	Goaf air-leakage velocity	Quantifies the velocity of air flowing through residual coal and determines the balance between oxygen supply and heat dissipation. Heat accumulation may occur when the velocity is too low, whereas excessive velocity supplies abundant oxygen; spontaneous combustion is most likely within a specific velocity range.
2	Width of the three zones and position of the oxidation zone	Defines the spatial ranges and dynamic positions of the heat-dissipation zone, oxidation zone, and suffocation zone. An excessively wide oxidation zone or a prolonged residence time significantly increases the probability of spontaneous combustion.
3	Matching degree between working-face advance rate and spontaneous-combustion period	Measures the time-race relationship between face advance rate and spontaneous-combustion period. A delayed advance rate exposes residual coal within the oxidation zone for a long time, allowing it to exceed the critical point of spontaneous combustion.
4	Influence of abutment pressure from adjacent working faces	Evaluates the damage to surrounding-rock integrity caused by stress redistribution induced by adjacent mining. Strong mining-induced pressure may form new air-leakage channels and worsen the fire-prevention environment.
5	Goaf water accumulation	Describes the range and depth of accumulated water. Water accumulation may obstruct the delivery of fire-prevention and extinguishing materials to the fire source and may also mask temperature through evaporation or form air-conducting fractures.

Among the environmental factors, the matching degree between working-face

advance rate and the spontaneous-combustion period is a hard constraint for goaf spontaneous-combustion prevention and control. Regardless of how strict the management measures are, if the face advance rate is slower than the natural spontaneous-combustion period of the coal seam, residual coal will inevitably accumulate heat and undergo spontaneous combustion within the oxidation zone.

4.4. Management-Factor Indicators

Management factors provide the organizational guarantee for the effective operation of the goaf coal spontaneous-combustion prevention and control system. In this study, ten management indicators are established, as shown in Table 4.

Table 4. Summary of management-factor hazard-source indicators.

No.	Indicator	Definition and description
1	Multi-departmental collaborative linkage mechanism	Evaluates the smoothness of information sharing and joint work among ventilation, geological surveying, mining, and other departments, breaking down departmental barriers and forming an integrated force for fire prevention and extinguishing.
2	Executability and update frequency of operating procedures	Measures whether operating instructions fit actual working conditions and are dynamically revised as mining processes change, ensuring that procedures effectively regulate employee behavior and prevent accidents caused by improper operations.
3	Coverage rate of the graded risk-control list	Quantifies the proportion of risk points incorporated into the red, orange, yellow, and blue graded-control lists and the implementation of corresponding measures, ensuring that all potential fire-source points remain under control and enabling proactive disaster prevention.
4	Closed-loop rate of hazard investigation and rectification	Reflects the whole-process completion rate from hazard registration to cancellation, emphasizing that every identified hazard must be rectified and every rectification must be accepted, thereby cutting off the chain through which hazards evolve into accidents.
5	Acceptance qualification rate of fire-prevention and fire-extinguishing projects	Assesses whether the construction quality of projects such as grouting works and stoppings meets design standards, ensuring that fire-prevention and extinguishing projects genuinely isolate oxygen, reduce temperature, and inhibit combustion.
6	Effectiveness of violation punishment and incentive mechanisms	Examines the guiding effect of punishment intensity and reward implementation on the participation of all personnel in safety management, thereby forming a positive situation in which employees dare not, cannot, and do not want to violate rules.
7	Safety-culture atmosphere and willingness to report proactively	Reflects an open culture that encourages proactive reporting of minor hazards without punishment, allowing numerous concealed early risks to be exposed and handled in time and building a mass-prevention and mass-control defense line.
8	Management attention to fire prevention and extinguishing	Represents senior management input into resource allocation and decision-making priority for fire-prevention and extinguishing work, directly determining the strategic status of safety work and the resistance encountered during implementation.
9	Proportion of professional technical personnel	Evaluates the proportion of professional engineers among relevant positions and their qualification levels, providing scientific technical support for fire-prevention and extinguishing under complex conditions.

10	Qualification and supervision intensity of outsourced construction teams	Reviews the qualifications of contractors and the strictness of quality and safety supervision by the contracting party during construction, preventing engineering-quality hazards caused by insufficient contractor capability.
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The closed-loop rate of hazard investigation and rectification is the core indicator for evaluating the effectiveness of the management system. Although the mine has relatively complete fire-prevention and fire-extinguishing hardware facilities, the effectiveness of this hardware depends entirely on human execution. This indicator focuses not only on how many problems are identified but also on how many are actually solved. A high closed-loop rate means that each minor hazard, from sensor failure and stopping leakage to rule-violating operations, can be recorded, rectified, verified, and closed, thereby blocking the pathway through which potential hazards transform into explicit accidents. It therefore serves as the bridge between technical equipment and safe production outcomes.

5. Results, Discussion, and Prevention-Control Recommendations

5.1. Mechanisms of Key Hazard Sources

Comprehensive identification of hazard sources for on-site goaf coal spontaneous combustion shows that environmental factors are the direct inducing conditions for spontaneous combustion, management factors are important root causes of continuous risk accumulation, equipment factors affect monitoring and treatment capability, and human factors run through the entire process of inspection, judgement, and emergency response. These four categories of factors are not independent of one another; rather, they jointly act on the accident chain of coal spontaneous combustion through multiple pathways.

At the environmental level, the matching degree between working-face advance rate and the spontaneous-combustion period is the key determinant of the residence time of residual coal within the oxidation zone. If face advance is slow, residual coal may still accumulate heat and increase in temperature owing to long-term low-temperature oxidation, even when air-leakage intensity is not high. At the equipment level, sensor integrity and early-warning-system response speed determine whether early anomalies can be captured in a timely manner; the reliability of standby power supply and emergency equipment determines whether the system can maintain basic response capability during disaster development. At the human level, the accuracy of early hazard recognition directly affects whether weak signs can be correctly interpreted. If personnel lack sensitivity to abnormal monitoring data, early oxidation signals may be misjudged as normal fluctuations. At the management level, the closed-loop rate of hazard investigation and rectification determines whether various problems can be rectified before an accident occurs and is the key bridge connecting technical measures with safety outcomes.

5.2. Precise Prevention-Control Pathways

To improve on-site prevention and control of goaf coal spontaneous-combustion risk, optimization should be carried out in the following aspects.

First, a dynamic all-factor hazard-source identification mechanism should be improved. Hazard-source identification should be transformed from an annual or staged static list into a dynamically updated list that changes with mining succession, geological conditions, the ventilation system, and monitoring data. Real-time recording and rolling assessment mechanisms should be established for factors such as advance-rate changes, stopping leakage, adjacent working-face mining, abrupt barometric-pressure changes, sensor anomalies, and unstable grouting effects.

Second, monitoring-data fusion and early warning should be strengthened. In addition to CO concentration and temperature, O₂ concentration, CO₂ concentration, indicative gases such as C₂H₄, Graham's coefficient, tube-bundle monitoring, infrared temperature measurement, and ventilation parameters should be comprehensively used to construct multi-indicator collaborative warning rules. When a single indicator shows only a slight anomaly but multiple indicators change synchronously, warning sensitivity should be increased to prevent early signals from being concealed by noise.

Third, differentiated treatment based on risk zoning should be implemented. Key prevention-control zones, general prevention-control zones, and stable zones should be delineated according to the three-zone distribution of the goaf, residual-coal enrichment areas, air-leakage channels, and the position of the oxidation zone. Targeted grouting, precise nitrogen injection, stopping reinforcement, and air-leakage sealing should be adopted in key areas; conventional inertization and monitoring should be maintained in general areas; and inspection and data review should be emphasized in stable areas. Zonal treatment can reduce resource waste and improve the pertinence of fire-prevention and fire-extinguishing projects.

Fourth, a linkage mechanism should be established between risk-evaluation results and production organization. When evaluation results show insufficient matching between the working-face advance rate and the spontaneous-combustion period, production organization should be optimized promptly to avoid long-term residence of residual coal within the oxidation zone. If face advance decreases because of geological structures, equipment failure, or transportation-system constraints, the intensity of fire-prevention and fire-extinguishing measures should be increased simultaneously, rather than separating production adjustment from safety treatment.

Fifth, closed-loop hazard management and responsibility tracking should be strengthened. For problems exposed by inspections, monitoring warnings, and special checks, the responsible person, rectification deadline, acceptance criteria, and reinspection records should be clearly defined. For repeated hazards of the

same type, cause analysis should be conducted to trace deep-seated problems in systems, training, equipment maintenance, or engineering quality, thereby reducing risk recurrence at the source.

Sixth, emergency resilience and extreme-scenario response capability should be improved. Drills should be conducted regularly for standby power switching, start-up of mobile nitrogen-injection equipment, replacement of failed grouting pumps, rapid sealing of stoppings, and personnel evacuation to test the operability of emergency plans. For key equipment, redundant configuration and regular trial-operation systems should be established to ensure uninterrupted monitoring and effective response during sudden events.

6. Conclusions

(1) The risk of goaf coal spontaneous combustion is a dynamic risk formed under the coupled effects of residual-coal oxidation and heat accumulation, air leakage and oxygen supply, mining-induced fractures, production organization, equipment reliability, and management execution. The traditional static management mode that relies on explicit monitoring indicators and empirical judgement cannot comprehensively identify concealed hazard sources and coupling-amplification effects under deep fully mechanized top-coal-caving conditions.

(2) Based on accident-causation theory and systems engineering principles, hazard sources for goaf coal spontaneous combustion can be divided into first-category material-energy hazard sources, second-category direct-trigger hazard sources, and third-category management-deficiency hazard sources. Constructing an indicator system around the four dimensions of human factors, equipment factors, environmental factors, and management factors helps identify and block the risk-evolution pathway of coal spontaneous combustion at the front end of the accident chain.

(3) The accuracy of early hazard recognition, reliability of standby power supply and emergency equipment, matching degree between working-face advance rate and the spontaneous-combustion period, and closed-loop rate of hazard investigation and rectification have critical effects on goaf coal spontaneous-combustion risk. These indicators represent early perception capability, system emergency resilience, the safety boundary of production organization, and management-execution quality, respectively, and should therefore be taken as priorities in risk evaluation and allocation of prevention-control resources in the studied mine.

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