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Impact Of Coal Mine Fires And Prevention Approaches: A Brief Review

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Abstract: Coal continues to be the most essential fossil fuel resource globally, representing 94% of reserves, while oil and natural gas make up just 6%, guaranteeing its steady industrial demand and utilization. While coal plays a significant role in the global energy landscape, it is also a key factor in the occurrence of spontaneous combustion within the mining sector, which can result in the ignition of fires in coal mines. Fires in coal mines present significant dangers to those working underground, and these dangers have a direct influence on both the global economy and the environment. The combustion processes emit harmful gases, including carbon monoxide, hydrogen sulfide, methane, carbon dioxide, sulfur dioxide, nitrogen oxides, and fine particulate matter, along with various by-products. This results in significant health risks, such as pneumoconiosis, alongside detrimental effects on the environment and human distress caused by heat, land subsidence, and pollution. Spontaneous coal combustion (SCC) serves as the main trigger for coalmine fires and tackling this issue can greatly diminish the occurrence of underground fires. Prioritizing prevention is crucial when addressing coalmine fires. Utilizing methods such as index gas monitoring, gravity heat pipes, oxygen inhibitors, gel suppressants, grouting, and foaming gels can significantly reduce the impact of SCC and coalmine fires. Moreover, significant attention must be directed towards the mechanical, electrical, natural, and human-induced factors contributing to mine fires in the effort to combat these blazes. Creating affordable techniques like foam, liquid nitrogen, and innovative fire-fighting technologies (such as the three-phase foam initiative) is essential for the prevention, detection, and extinguishing of difficult-to-find underground fires. Enhancing safety laws and creating an autonomous monitoring system for coalmine safety will bolster enforcement efforts. Effective implementation of ongoing safety training, thorough evaluations, and heightened awareness can significantly decrease the occurrence of coalmine fires when managed correctly from an administrative standpoint.

Keywords- Coalmine fires; Spontaneous coal combustion; Fire prevention; Methane explosion; Particulate matter.

I. INTRODUCTION

Coal is one of the most critical and primary energy resources in the world [1]. Among all proven fossil fuel reserves, coal accounts for 94%, whilst oil and natural gas account for 6% only [2]. Thus, the demand and use of coal in industries would remain inevitable. Coal can be responsible for most of the spontaneous combustion in the coal mining environment, leading to fire outbreaks (coalmine fires). These fires, on most occasions, endanger safety and stability, take lives, cause economic loss (damage coal resources) and severe environmental hazards (produce large volumes of smoke and toxic gases), particulate matter (PM) among others [3]. Mine fires represent one of the greatest threats and primary natural disasters to those working in the underground mine environment. Mine fire accidents are observed in almost all coal-producing and bulk utilization countries, including China, Australia, the US, Indonesia, and India. The majority of these mine fires are caused by the spontaneous combustion of coal [4]. Once the spontaneous combustion (SC) of coal occurs, it causes disasters such as fires, dust explosions, and gas explosions, which can even cause heavy casualties and property losses that are difficult to estimate [5-9]. Therefore, it is incumbent on the major producers and users like China, the U.S., Australia, and India to adequately fight the spontaneous combustion of coal, considering the challenges it poses. Much research has been conducted to mitigate the SCC in an attempt to prevent and control mine fires, as discussed in 4.1 and 4.2. These prevention approaches span from methods of prediction, prevention, and control. In addition, many techniques have been used to control mine fires traditionally but come with some shortcomings as presented in Table 1-1.

1.1. Countries with High Incidence of Coal Mine Fires

Per the production and utilization of coal, the main countries that face numerous coal mine fires in the world include: China, the U.S., Australia, Indian, Indonesia, and South Africa. All these countries have experienced unprecedented coal fire episodes that raise concerns, with the genesis of most mine fire extinguishment approaches deriving from their origin. A brief background of some of these spectacular fire events is presented from 1.2.1. to 1.2.6.

Table 1-1 Some traditional technologies for mine fire control and their limitations

Traditional Technologies	Limitation	Reference
Ammonium salt gel	Can release toxic gas	[4]
Inorganic gel (e.g., inorganic silicone gel)	Poor water retention and being prone to cracking after dehydration of the cured gel	[4, 10]
Composite slurry	Strength not high	[11]
Chemical slurry	Some expand rapidly, leading to blockages in pipelines during grouting.	[12]
Physical inhibitors	Easily run off with temperature increase, and free radical scavengers are mostly expensive and can give off ammonia (a toxic gas)	[4]
Gelatum (Composed of silicate and ammonium salt)		[13]
High molecular gelatum	Expensive	[13]
Foamed resin	Expensive	[13]
Inert gases	Are prone to diffuse with air leakage and cannot remain in the area where they are needed	[13]

1.1.1 China

China is one of the countries that have suffered badly from the serious hazards of coal fires since the 1960s [14]. The fatal number of fire accidents, roof accidents, and gas accidents is the highest in China, vis-à-vis the high demand and production of coal, especially in underground mines. Based on statistics of accidents and rescue experience, only less than 10% of miners die at once on the field because of explosions and collapse, mostly are caused by exhausted oxygen surrounding and high concentrations of toxic and harmful gases and blocked escape routes due to fire and explosions, which form the direct cause of casualties [15].

Earliest coal fires

Coal fires in China were recorded as early as 1600 years ago in a book called “Commentary on the Water Classic” (or “Shui Jing Zhu”), compiled by LI Daoyuan during the Northern Wei Dynasty (386-534 AD) [16]. Coal fires located in Kuche County and Baicheng County of Xinjiang Uyghur Autonomous Region were described in this book. During the last four decades, over 1.86 km2 of coal fires were located in Baicheng County, and one of them, Tielieke (0.92 km2), considered the second largest coal fire area in China, was extinguished in 2007[17]. In the Northern Song Dynasty, Wang Yande (939-1006 AD), an officer in Xinjiang, recorded ammonium chloride (NH_4Cl) released by coal fires in Jimusaer County and Qitai County. According to a coal fire survey in Xinjiang in 2008, there were ~ 0.27 km2 affected by coal fires in Jimusaer County and Qitai County [17]. Additionally, the travel documents of Marco Polo (1254-1324 AD) mentioned “burning mountains along the Silk Road”, which indicates that coal fires occurred in the Tarim Basin and Gansu

Province. Zhang et al. [18] reported that paleo coal fires in Xinjiang date back as far as the Pliocene, Pleistocene, and Holocene ages.

Mine fires in China are mostly concentrated in the north due to coal bed distribution, mining activity, and climate conditions. Some background on a few of the very important spots is provided below.

Inner Mongolia Autonomous Region

Coal fires in Inner Mongolia are mainly distributed in the Ordos district, Wuhai-Haibowan district, and Alxa League. The main affected coalfields are the Baijigou, Wuda, Zhuozishan, Jungar, Dongshen, and Shiguai coalfields. Coal production in Inner Mongolia has increased from 602.8 Mt/a (the second largest production in China, followed by 615.35 Mt/a in Shanxi Province) in 2009 to 1.08 Gt/a in 2012 (China Economic Information Network, 2013), resulting in the rapid development of coal fires. As it stands now, Inner Mongolia experiences the most coal fires in China. There are 230 individual fires (coal seam fires and coal mine fires) in Inner Mongolia affecting an area of 63 km2. By 2011, 42 km2 were extinguished. For instance, in the Wuda coal fire area, the national government and Shenhua Group to extinguish the fires invested over 48.51 million US dollars.

Xinjiang Uygur Autonomous Region

Economic development, coal production, and fire-fighting activities are the main factors that have influenced the current coal fire distribution and development over the last decade. It is imperative to conduct coal fire surveys to better understand the characteristics that influence its distribution. For example, in the Xinjiang Uyghur Autonomous Region, three coal fire surveys have been undertaken since 1981. The first survey recorded 42 coal fire areas. Later, 35 and 39 coal fire areas were surveyed in 1995-1997 and 2008[17], respectively. According to the surveys conducted in 2008, coal fires were distributed mainly in the Junggar (note that it is different from the Jungar Coalfield located in Inner Mongolia Autonomous Region) and Yili coalfields. The average depth of coal fires was about 50-60 m. Total fire area and burnt coal amount were 9.06 km2 and 8.13 Mt, respectively. Local and national [19] efforts to fight coal fires in Xinjiang in the last three decades invested over 69.72 million US dollars (434.5 million Renminbi (RMB)). Extinguished large coal fires include Liuhuanggou (1.83 km2, the largest coal fire in China), Tielieke, Keerjian, Yangxia, and Kueraken.

Ningxia Hui Autonomous Region

Five coalfields, Ruqigou, Redaolin, Manlintan-Shitanjing, Hulusitai, and Xianshan, in Ningxia were reported to be affected by coal fires after a survey in 2004[20]. The Ruqigou Coalfield was the largest coal fire area with 15 active fires and 12 extinct fires in 2004. 12.2 million US dollars were invested to fight coal fires in Ruqigou. Currently, most coal fires have been managed and extinguished due to the advancement in control methods [21]. Fig. 1-1 presents some of the coal mine fires that occurred in the north of China.

Fig. 1-1 Lignite coal fire in the Jiangjungebi open pit coalfield, Qitai, Xinjiang. The coal is thought to have been mined during the Tang and Song Dynasties. (a) Cracked and collapsed sandstone from the coal fire. The length and width of the crack are 15 m and 1 m, respectively (b) Six-meter-long crack caused by the coal fire (c) White mineral(s) encrusting the top of gas vents (5-20 cm in diameter) in a coal waste heap (d) A white mineral (possibly mirabilite) nucleated in association with coal-fire gas [22].

1.1.2. USA

Before 1909, an average of 500 fires occurred every year. Glover [23] gave an account of the Pennsylvania coal fires that occurred in 1869 in Avondale Mine, Plymouth, when a ventilating furnace ignited wooden support, suffocating 110 men trapped underground [24]. In 1909, the Cherry Mine fire in Illinois, which took 259 lives, was one of the compelling reasons for establishing the U.S. Bureau of Mines [25]. Starting from 1910, the U.S. Bureau of Mines and NIOSH have conducted numerous studies to eliminate fires in underground mines. Their initial studies focused on investigating the causes of mine fires to prescribe appropriate prevention methods for fires, SC, and mine fire rescue, all aimed at improving the safety in mines. In the 1950s, research characterized the flammability of gases, dusts, and vapours. The 1960s emphasized mine fire prevention, the hazards of combustible materials used in mines, and mine fire extinguishment [26]. From 1990-2007, 1601 reportable fires (an average of 89 fires per year) occurred in the U.S. mining industry [27]. Counting from 1990 through to 2001, 1060 fires were recorded, of which 560 injuries and 6 fatalities were recorded at a U.S. mine [28]. In 2006, an underground mine fire at a West Virginia Coal Mine took 2 lives [26].

Since the institution of the U.S. Bureau of Mines and NIOSH in 1910, the industry has seen a progressive decline in mine accidents, which can be attributed to the rigorous and comprehensive implementation of preventive and control measures. To realise this achievement, the NIOSH did the following, as enumerated below [29].

(i) Conducted research aimed at ensuring that fire-safe materials are used.
(ii) Ensured that combustibles are properly handled and stored.
(iii) Ensured that mechanical and electrical equipment is properly used and maintained.
(iv) Ensured personnel are adequately trained and educated in fire safety practices.
(v) Developed fire-sensing systems.
(vi) Provided guidelines for selecting and using these systems.
(vii) Investigated the principles of fire dynamics and the interaction of gaseous or chemical.
(viii) Explored the role of ventilation in fire control and extinguishment, highlighting how various fire and smoke mechanisms can affect these interrelationships with an expanding flame.

1.1.3 Australia

Luhar et al. and Teague et al.[30, 31] reported that, on 9 February 2014, under hot and windy weather conditions, embers from two bushfires burning near the coal mine spotted into the northern face of the open-cut brown mine adjacent to the Hazelwood Power Station in the Latrobe Valley in Victoria, Australia, and the exposed coal caught fire. The 3,138 ha mine caught fire and burned for six weeks, resulting in the nearby town of Morwell and other areas of the Latrobe Valley being covered in plumes of smoke [32] as shown in Fig. 1-2.

Due to the strong south-westerly winds with wind gusts up to 74 kmh-1, the fire spread rapidly and extensively throughout the mine and was well established by early evening [33]. Because of difficulties in quenching it, the fire in the coal batters burned for 45 days and was officially declared extinguished on 25 March. It was the largest and longest burning mine fire that had occurred in the Latrobe Valley to date. The Hazelwood open-cut coal mine is the most talked-about mine fire in Australia and its direct and indirect impact has been extensively researched by a number of scholars.

Fig. 1-2 Hazelwood Open-Cut Coal Mine (left) and Morwell exposed to the plume from the Hazelwood coalmine fire. (Source: Modified from [30])

1.1.4 India

In Indian coal mines, mine fires have become a very problematic issue, numbering more than 200, for both surface and underground. The most important fire-affected coalfields include Jharia (Fig. 1-3), Raniganj, Talcher, Ib Valley, Chirimiri, Singrauli, and Ramgarh. In Indian coal mines, most fires occur due to SC, an oxidation process of coal [34]. Singh et al.[34] enumerated the main reasons for the occurrence of fire due to spontaneous heating in Indian mines as follows:

(i) thick coal seams; (ii) plenty of coal fines left in the goaf; (iii) presence of contiguous seams, some of which are burning; (iv) shallow depth; (v) proximity of intake and return; (vi) high pressure differences between the intake and return; and (vii) high SC susceptibility characteristics of most of the coal.

Fig. 1-3 spontaneously ignited mine fire at Jharia Coalfield, India [35]

The Jharia Coalfield (JCF), located in the Dhanbad district, north of the Damodar River is India's largest and primary source of coking coal. Coal fires in Jharia can be traced back to 1916. In 2011, more than 70 mine fires were reported from the 23 large underground JCF region. SCC [36] ignited most of the coal fires in JCF.

1.1.5 Indonesia

Indonesia’s coal fires are one of the unintended by-products of land conversion and agricultural fires. Responding to Indonesia’s 1997-1998 fires and haze crisis, the US Government convened an interagency working group to develop proposals for follow-up assistance. Between 1998 and 2002, the Office of Surface Mining (OSM) provided Indonesia with the capability to take quick action on coal fires that presented threats to public health and safety, infrastructure, or the environment. Indonesian coal fires occur in both mined and unmined coal; the fires of greatest concern to the OSM and the Ministry of Energy and Mineral Resources (MEMR) were in unmined coal. Of the 263 coal fires investigated in Indonesia, all began along unmined coal outcrops and resulted from forest, bush, or trash fires. From experience, it was noted that this type of coal fire could smoulder and burn for decades, remaining sources of ignition for new forest fires and probably new coal fires [37].

1.1.6 South Africa

Disasters such as those at the Kinross Gold Mine in 1986, in which 177 miners died, have focused attention on the hazards faced by underground miners in South Africa [38].

SC and burning of coal in the Sasolburg Coalfield were first recorded in 1985 in unmined coal in the New Vaal colliery. Large fires flare up from the exposed middle seams of old workings. The fire was extinguished using a cladding and dozing technique, i.e., sand dumped onto the burning coal seam to choke the fire. However, by February 1990, the fires had spread, and cladding and dozing operations were no longer able to handle the coal fire safely. In 1990, sand was dumped directly over the high wall, closing off the old workings as quickly as possible after they had been exposed [39].

This review aimed at discussing some of the coal mine fire events in the major countries that produce (some for export) and use coal. It further considers the causes, impact, prevention, and control of coal mine fires. SCC is looked at as the principal initiator of mine fires and proposes some administrative management aside from the existing engineering methods employed that can help reduce mine fires to save life, the environment, money, and most of all the health-related hazards. Below is the enumerated, precise, and concise outline in Fig. 1-4.

(1a) Coal seam, (1b) possibility of forest or bushfires igniting exposed coal seams, and (1c) other factors or sources that can directly cause mine fires or indirectly initiate SCC, which can eventually end in mine fires.

(2) Fine coal at various places (i.e., in transport, gobs, goafs, working faces, gangues, abandoned mines), such as storage and utilization points.

(3) Fine coal exposed to open air, where oxidation is initiated.

(4) Prediction and prevention methods employed to handle SCC, including: Management and supervision, gel suppressants, oxygen inhibitors, grouting and foaming gels, gravity heat pipes, index gas monitoring, etc. Thus, with these interventions, SCC is predicted and prevented.

(5) Without these interventions, self-heating is initiated and may lead to the following;

(a) SCC

(bi) SCC leads to environmental pollution and the greenhouse effect with serious health hazards due to the release of NGs, GHGs, and PM (especially PM2.5).

(bii) SCC can bring about a methane explosion should there be any leakage.

(ci) Ultimately, the SCC results in underground coal mine fires with a couple of these, i.e.,

(cii) subsidence, loss of life, dust explosions, ceiling collapse, loss of valuable resource (coal), increased budget, etc, as adverse consequences.

(6) The underground mine fire can be controlled or extinguished by using the three-phase foam and the MS/CMC-Al3+ per this write-up.

<u>NOTE</u>: Other control and extinguishing methods and formulations have been researched, but more emphasis is laid on SCC for the prevention of coal mine fires.

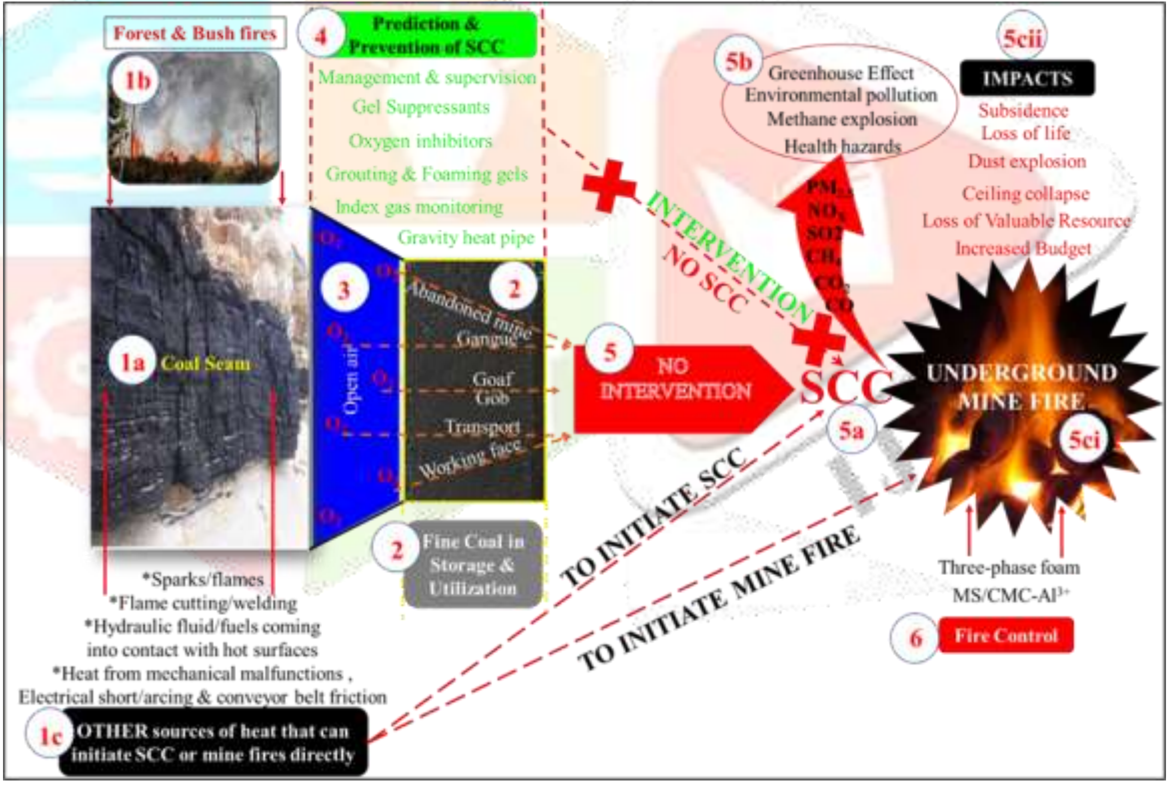

Fig. 1-4 Schematic outline of a possible case of underground mine fire initiation, ignition, prediction, prevention, and control, as well as the adverse effects when SCC or the fires occur

II. CAUSES OF COAL MINE FIRES

Explosions and fires have been recognized as the primary causes of mine accidents and are deemed to be thermodynamically driven accidents due to their identical thermochemical essence of combustion, interchangeability, and producing similar gaseous hazards [40]. Coal dust explosions have been reported to be the initiator of about 59% of the fires and explosions that claimed over 100 lives. Even though methane gas is noted to cause mine explosions, it has been observed that some explosions occurred in coal mines with low methane gas emissions.

NIOSH [41] reported that the leading causes of U.S. mine fires include flame cutting and welding operations, frictional heating and ignitions, electrical shorts, mobile equipment malfunctions, and SC. Apart from factors influencing the spontaneous combustion of coal, forest fires, lightning, and human activities such as mining activities, discarding of burning cigarettes, burning trash piles, and ignition of coal for heating, cooking, and generating 'Red Dog' for ash used for traction on ice also trigger coal fires [16].

2.1 Spontaneous Coal Combustion (SCC)

Subsurface fires are a common threat for coal mining, since SCC can easily result in gas combustion and explosion [42]. SC is one of the principal dangers and major problems faced in the coal mining industry over the years, which directly affects the coal value chain [43, 44], and takes place in nearly every coalfield worldwide [43]. Though the frequency and extent of the incidents vary from country to country, with the growing mining depth and the increasing intensity, mine fire has become inevitable and one of the main disasters in coal mines [45, 46]. SCC not only consumes valuable coal resources, but the production of environment-polluted toxic fumes such as CO, CO2, SO2, NOX, and H2S, which may create both health and environmental hazards [47]; SCC may also lead to gas explosion, roof falls, and other accidents, causing casualties. Therefore, it significantly damages and influences the atmospheric environment, vegetation, water, and land resources, also induces various geologic hazards.

Self-heating of coal begins when sufficient oxygen from the air is present to support the reaction between coal and oxygen. The heat produced by low-temperature oxidation of coal is not sufficiently dissipated either by conduction or convection, hence causing the temperature of coal accumulation to exceed approximately 80 degrees Celsius. Eventually, coal will start to smoulder and burn [48, 49]. Experimental studies of coal established that the oxidation process occurs in four stages, namely: (1) physical adsorption of oxygen, (2) Chemical absorption, (3) Self-heating temperature is reached, and (4) Temperature exceeds approximately 150 degrees Celsius. The chemical reaction is expressed as Eqn. (1) [50].

$$\text{Coal} + \text{Oxygen} \rightarrow \text{Oxygen} + \text{Heat} \rightarrow \text{Gas product} \qquad (1)$$

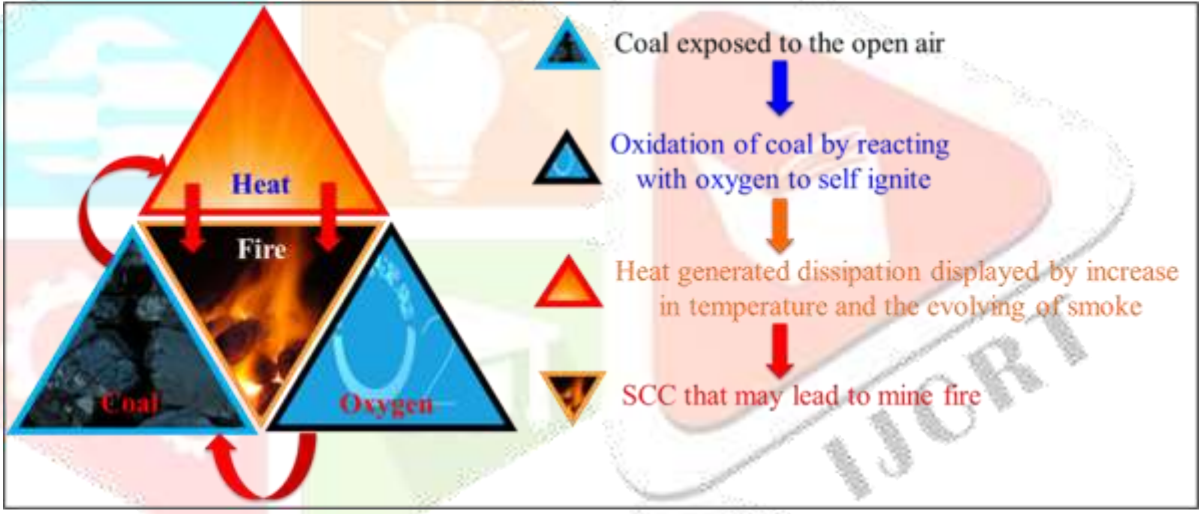

Fig. 2-1 The process of SCC

Fig. 2-1 gives a pictorial presentation of the SCC process of coal exposed in open air. Coal seams with SC tendency develop into self-ignition by gathering four factors: plenty of broken coal; continuous air supply; heat storage, and enough time for coal's oxidation [51]. The continuous occurrence of abandoned spoil heaps, old workings, waste dump fires, etc., requires precautionary measures to prevent the event of spontaneous combustion in coal mines [44]. While in Europe, the U.S., China, India, and Thailand, several methods have been employed to minimise these incidences, but the problem persists [44].

SC is the major cause of underground fires, and a coal dust explosion has the potential to turn an ignition or explosion incident into a major catastrophe [52].

2.2 Human Factor

Mine fires cause devastating accidents, with some instances accounting for unprecedented deaths, especially in China. Research conducted on fatal accidents in China [53] from 1980-2000 revealed that the human factor was the key direct reason and accounted for up to 97.67% of total accidents. Duzgun and Yaylaci [54] explored the fire in the Soma Mine disaster in Turkey and established that problems of emergency management of decision makers led miners to have a false sense of safety. Chen [55] researched the 10-year tendency of China coal mine accidents and the characteristics of human factors, and concluded that human factors accounted for 94.09%, of which intentional violation, mismanagement, and defective design accounted for 35.43%, 55.12%, and 3.54%, respectively.

2.3 Methane and Explosions

Methane is abundantly available in coal mines; therefore, it is easily ignitable and may lead to fires and coal dust explosions. In underground coal mines, an explosion can result in a fire and vice versa. Underground spontaneous heating is also possibly coupled with methane leakage and ignition [56] and may generate a mine fire as a result. Dzuzovic [57] reported that a methane ignited and the explosion killed the entire work face crew in the Soko Coal Mine in Serbia in 1974. Additionally, 14 lives were lost, and several workers were injured.

2.4 Coal Dust Explosions

Although explosions have always constituted a major hazard in coal mining, the dangerous role of coal dust was not recognized for many years. At first, all explosions were thought to be due entirely to the ignition of firedamp, essentially a mixture of methane and air. During the early part of the 19th century, several British and French investigators, notably Michael Faraday, observed that in some explosions, coal dust helped to spread the flames. Further proof of this was obtained in experiments in several countries, and eventually it was established that coal dust alone, in the absence of flammable gas in the mine air, can produce explosions when dispersed and ignited [58].

De-Rosa [59] analysed mine fires for all U.S. underground and surface coal mining categories from 1990-1999, the ignition sources that caused most of the fire injuries were flame cutting/welding spark/slag/flames, hydraulic fluid/fuel sprayed onto equipment hot surfaces, and flammable liquid/refuelling fuel on hot surfaces. Other ignition sources considered were heat sources, mechanical malfunctions, electrical short/arcing and coal dust explosion, and conveyor belt friction.

Pomroy [60] indicated that from 1978 to 1992, the most frequent burning materials in underground coal mines in the U.S. were coal and coal dust, electrical insulation, oil and grease, conveyor belts and rollers, wood, rubber hoses, and tires. Isolating incidents of coal dust explosions also has its difficulties. Statistics are normally available for reported ignitions and explosions, or fires caused by flammable gases. It would appear that, in the majority of cases, methane is responsible for the incident. Only in particularly violent incidents is the mechanism of the incident extensively researched, and in those cases, a secondary coal dust explosion is usually suspected. SC is the major cause of underground fires, and a coal dust explosion has the potential to turn an ignition or explosion incident into a major catastrophe [52].

2.5 Forest Fires and Droughts

In Indonesia, the most damaging fires occurred in 1982-1983, 1987, 1991, 1994, and 1997-1998. In all these years, the fires were exacerbated by drought brought on by the El Niño Southern Oscillation (ENSO) [61]. In ENSO years, the delay of the monsoon means that fires burn for several months longer than usual. In addition, because the land was unusually dry, fires burn out of control more easily, sometimes escaping into peat forests, where they burn underground and may ignite shallow coal seams [62]. Teague et al. [31] reported that, in early 2014, two bushfires were “spotted” in an open-cut brown coal mine adjacent to the Hazelwood Power Station in the Latrobe Valley in Victoria, Australia, as shown in Fig. 1-2.

III IMPACT OF COAL MINE FIRES

3.1 Health Impact

The coal dusts, smoke, toxic fumes, GHGs, and PM emitted from coal mine fires have severe health impacts that range from respiratory to cardiovascular diseases, with some other systemic diseases. The commonest ones are the pneumoconiosis, also called Black lung disease, and silicosis; both importantly reduce the life expectancy rate since they cannot be cured. PM emissions also affect expectant mothers and foetal development.

3.1.1 Particulate Matter (PM)

PM is one of the most important and main aerosols that are emitted from the coal mine fires. PM or, more appropriately, atmospheric aerosol is currently a subject of extensive research. PM is a complex atmospheric heterogeneous mixture of inorganic and organic particles differing in size, origin, and chemical composition that exist in either the solid or liquid state [63]. Among all air pollutants, fine PM2.5 is the most harmful pollutant with regard to human health and may induce a sequence of diseases [64, 65]. It has been estimated that nearly 80% of premature deaths resulted from air pollution attributed to exposure to PM2.5 pollutions [66].

Exposure to high levels of PM can generate various human health problems, such as respiratory diseases [67] and cardiovascular diseases [68].

Fine PM may also contain condensates of volatile organic compounds, volatilized metals, and products of incomplete combustion. The PM emitted from coal combustion is composed of three constituents as presented in Table 3-1. Coal dust coming from mine fires can result in several diseases, which include both respiratory and cardiovascular diseases. A typical one is the Coal Workers' Pneumoconiosis (CWP) discussed below.

Coal Workers' Pneumoconiosis (CWP)

CWP is an incurable disease commonly referred to as "black lung disease" and is a nodular interstitial lung disease that is caused by long-term inhalation of coal dust [73], and in severe cases may lead to progressive massive fibrosis [74]. Over time, continued exposure to the coal dust causes restrictive impairment, scarring in the lungs, and impaired ability to breathe. It may be acute (cause death within months) or chronic (cause death after many years), depending on the extent and severity. CWP, an occupational lung disease, is most common among coal miners.

Coal is a combustible, carbonaceous, sedimentary rock composed mostly of carbon and hydrogen [75]. The coal that forms with greater combustion capacity has the highest tendency of causing CWP, due to having more surface free radicals [76]. Coal mine dust is a complex and heterogeneous mixture containing more than 50 different elements in and around the coal seam that include carbon, quartz, silicates (such as kaolinite and mica) [77], and other trace elements such as boron, cadmium, nickel, iron, antimony, lead, and zinc, among others [78].

Table 3-1 Constituents of PM emitted from coal combustion

Content	Characteristics
1. Unburnt coal	*Produced from the incomplete combustion of coal, the mass fraction of which can exceed 90% of the total PM, can drop to less than 1% under good combustion conditions. The unburnt carbon, also termed as soot, consists of grape- or chain-like agglomerates of primary carbon-enriched particles, which are in the chemical form of polycyclic aromatic hydrocarbons (PAH), existing as a potentially carcinogen and mutagen to humans [69] due to their polarity [70, 71].
2.Inherent mineral matter	*Particle size less than 10.0 nm may escape the burning char and transfer into PM without phase change [70].
3. Volatile matter	*Most of the heavy metals within coal initially vaporize in the flame zone; the resultant metallic vapour then undergoes homogeneous nucleation to form an ultrafine aerosol having a size of 10 to 30 nm. In the post-flame, the combustion gases cool rapidly, the condensed aerosol grows continuously by heterogeneous coagulation; the resultant agglomerates have a mean size of about 1.0 to 2.0 μm [72].

Initially, CWP was thought to be a variant of silicosis due to its similarities in chest radiographs, and coal dust was considered innocuous [73].

Mo et al.[73], After conducting a research survey using meta-analysis identified specific factors such as duration of dust exposure, coal rank, stages of CWP, types of work, and coal mining categories were identified, which were significantly associated with the high risk for CWP.

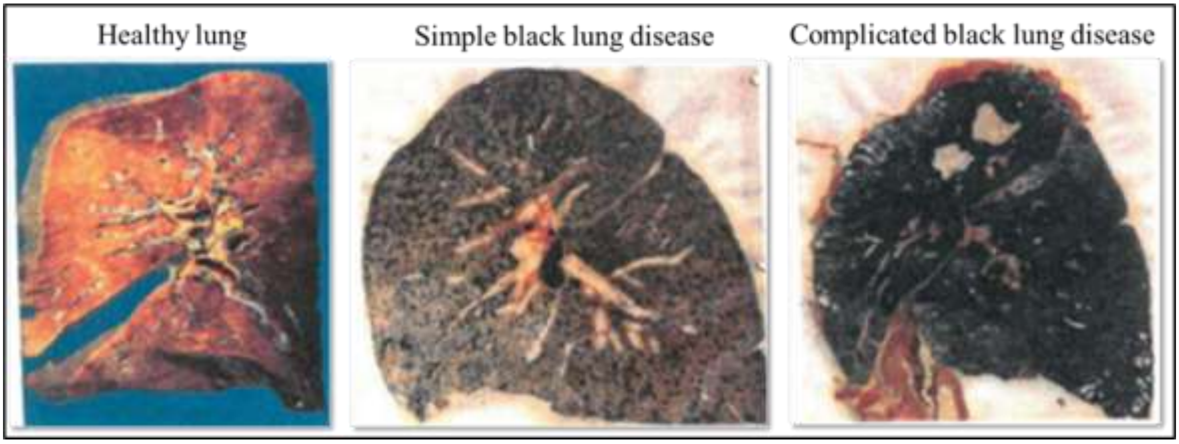

Fig. 3-1 Healthy lung, simple black lung disease, and complicated black lung disease (Source: Modified from [79])

Fig. 3-1 shows a healthy lung, a simple black lung disease, and a complicated lung disease. In the most complicated form of the black lung disease, the volume of the lungs shrinks and causes damage to adjacent lung tissue, making breathing difficult and decreasing gas exchange [79]. Complicated black lung disease can develop within 5 years with massive fibrosis in underground miners.

Maternal Exposure to PM

Several studies have been conducted to understand the impact of maternal exposure to short- to medium-term episodes of poor air quality emanating from wildfires, agricultural fires, deforestation fires, and particulate air pollution from volcanic eruptions, on neonatal outcomes such as birth weight, low birth weight, preterm birth, and gestational length. Drawing inference from these studies is challenging, due to the limited number of studies and their heterogeneous classifications of exposure and/or outcome. However, findings suggest an adverse association with foetal growth and possibly preterm birth. Exposure in the second and third trimesters appeared to be of greatest relative importance [80, 81].

The Hazelwood coal mine fire was an unprecedented event in Australian history that resulted in the surrounding towns in regional Victoria being covered in plumes of smoke and ash for six weeks in 2014. Based on this, Melody et al. [82] explored the association between maternal exposures to coal-mine fire attributable PM2.5 and neonatal outcomes, including foetal growth and gestational maturity. Secondly, they wanted to determine whether any subgroups within the pregnant population were more susceptible to adverse neonatal outcomes in association with coal mine fire smoke exposure, such as extremes in reproductive age, gestational diabetes mellitus, hypertensive disorders of pregnancy, maternal smoking in pregnancy, or infant sex. The findings suggested no evidence of an association between maternal exposure to fine PM from coal mine fires and foetal growth rate. However, there was no clear evidence that the extent of exposure was important. However, women with gestational diabetes mellitus appeared to be more susceptible to possible trophic effects of exposure [82].

Due to the knowledge and the severe effects of PM2.5, there may be a higher likelihood of association between maternal exposure to coal-mine fire attributable PM2.5 and neonatal outcomes, including foetal growth and gestational maturity, considering long-term exposure. More studies need to be done to ascertain this possibility to equip public health administrators and service providers to better understand the possible impact and for its management.

3.2 Environmental Impact

Coal fires burning around the world are an environmental catastrophe characterized by the emission of NGs (including CO, SH2), GHGs (including CH4, CO2, SO2, NOx), PM, and condensing by-products. Underground fires ignited by natural causes or human error are responsible for atmospheric pollution, acid rain, perilous land subsidence, and increased coronary and respiratory disease. They consume a valuable energy resource, destroy floral and faunal habitats, and promote human suffering because of heat, subsidence, and pollution [37]. Some direct and indirect impacts experienced by miners, humans, and other living organisms (i.e., both animals and plants) are considered in Fig. 3-2. As mentioned earlier, these GHGs, NGs, and PM affect both the environment and its inhabitants, ranging from ill health to global warming and climate change, poisoning of the arable lands, and burning of forests, etc.

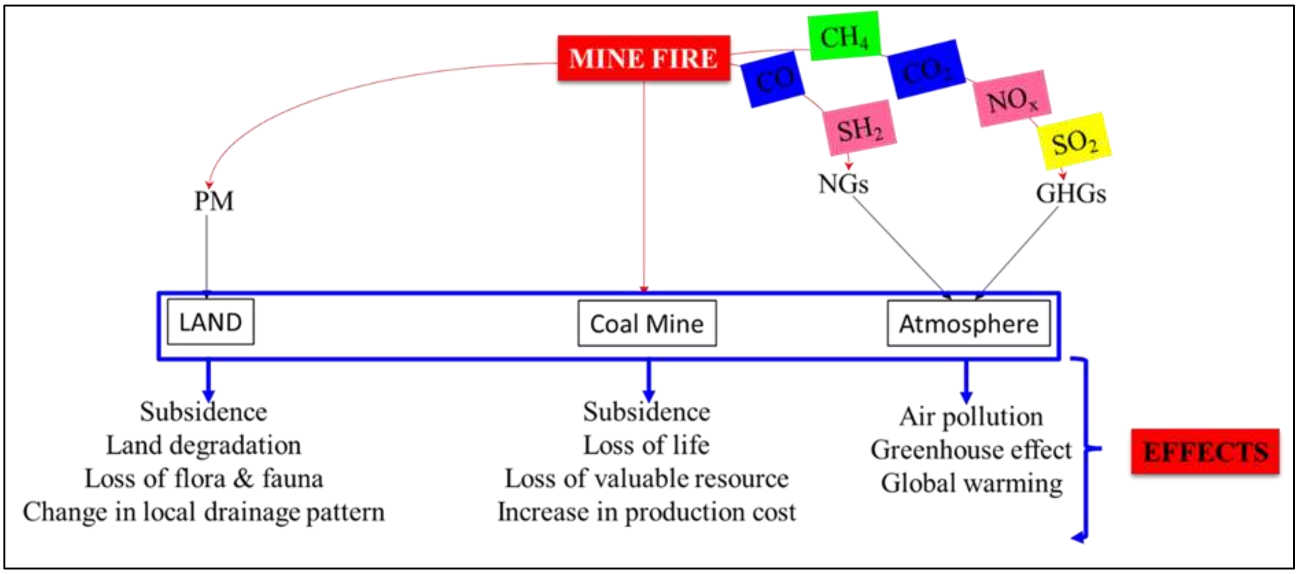

Fig. 3-2 Environmental impact of coal mine fires [129]

Over 200 coal fires in Pennsylvania have contributed to making it one of the leading acid-rain producers in the U.S. [83]. Acids, aerosols, and toxic PM emanating from coal fires may be transported long distances, for instance, the adverse effect of such pollutants on 88 cities in China, with the effects of acid rain spilling over into Japan, Korea, and the Philippines [84]. In Indonesia, coal fires threaten East Kalimantan's shrinking ecological resources in the Sungai Wain Nature Reserve (Fig. 3-3) and Kutai National Park. Sungai Wain had one of the last areas of unburned primary rainforest in the Balikpapan-Samarinda area with an extremely rich biodiversity and many rare and endangered wildlife species (i.e., of the 20,000 orangutans estimated to remain in the wild, approximately 15000 are in Kalimantan) [85].

PM from coal mine fires can cause atmospheric visibility impairment by scattering and absorbing light [87]. It can also influence climate directly by scattering and absorbing solar radiation and indirectly by modifying clouds' microphysical properties of albedo and lifetime [88].

Fig. 3-3 Fire incidents in Sungai Wain Left: Before and Right: After [86]

3.3 Impact on Mining Operation

Song and Kuenzer [21] reported that the total fire area and burnt coal amount were 9.06 km2 and 8.13 Mt, respectively. Most of the indirect impact has to do with influencing the mine's budget and paying compensation to the casualties. In addition, medical bills can be captured as another area. Similarly, the investment made to extinguish mine fires, as discussed in 3.4, can be included as an impact. Loss of coal resource is always a big blow and unavoidable in the event of fires.

3.4 Economic Impact

Coal fires are an environmental and economic problem of international magnitude [36]. Coal fires are observed in the major coal-producing countries, including China, the U.S., Australia, South Africa, India, Indonesia, etc., as depicted in Fig. 3-4[89].

The largest coal fires are recorded in China, the U.S., India, South Africa, and Indonesia [35]. Stracher [90, 91] reported that the economic losses incurred as a result of coal mine fires are extensive, with those of China estimated at US$125-250 million, and those of the U.S. estimated at US$651 million, essential to contain or extinguish coal fires. Similarly, in India, ~1453 million tons of coal are locked up in 70 fires in the Jharia coalfield alone.

Song and Kuenzer [21] hinted that 12.2 million US dollars were invested to fight coal fires (i.e., 15 active fires and 12 extinct fires) that were encountered in Ruqigou in 2014. Similarly, over 69.72 million US dollars

(434.5 million Renminbi) were invested by local and national [19] to fight coal fires in Xinjiang in the last three decades. In addition, for instance, in the Wuda coal fire area, the national government and Shenhua Group to extinguish the fires invested over 48.51 million US dollars.

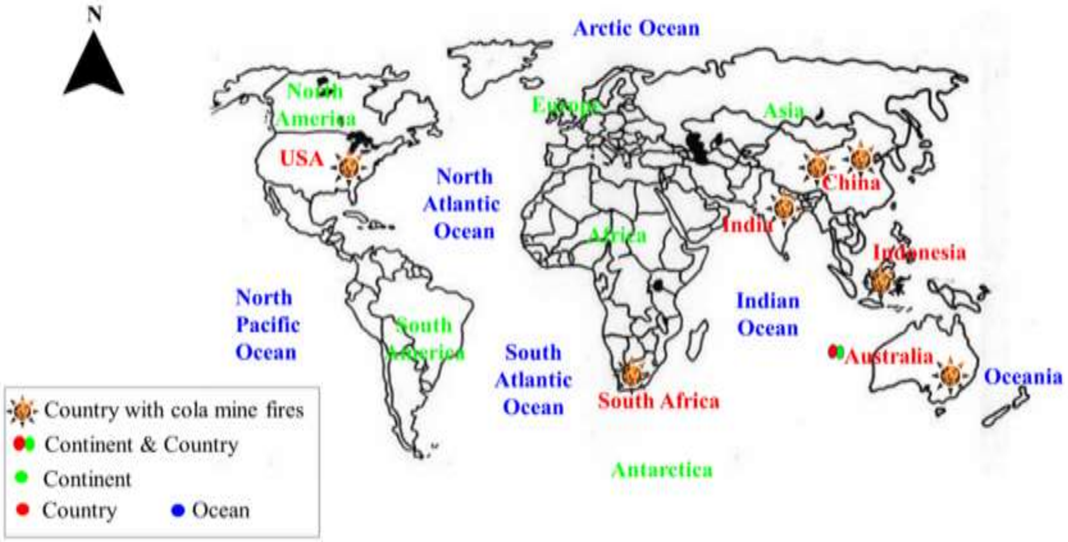

Fig. 3-4 Coal fires around the world [129]

IV. PREVENTION AND CONTROL OF MINE FIRES

To manage and prevent coal mine fires, much needs to be done to predict, prevent, and control SCC, as discussed in 4.1 effectively and constructively.

4.1 Prevention of Coal Mine Fires

This section outlines the frequent practical methods used to discover the propensity of coal to self-heat and examines the external factors that can combine to bring about the SC. Furthermore, by understanding why and how coal undergoes combustion spontaneously, coal users can plan, predict, and avoid accidents that could be costly in terms of coal lost, emissions of pollutants, health hazards, and ultimately, the risk of fires [92].

Currently, most approaches researched to tackle and curb the spontaneous combustion of coal, which is notably the main cause of mine fires to the barest minimum combine coal assessment and site-specific parameters, to design and make systems that signals, trigger alarms, temperature or chemical sensors etc., which are veered towards policy and legislation in countries like China and Australia. These standards, when incorporated into the mining and management of the industry, would not only predict and prevent incidents and accidents but also serve as a foundation to be built upon to upgrade the existing scope of knowledge and practice for better advancement of the coal industry.

4.1.1 Index Gas Monitoring

Analysis of the index gases of coal for the prevention of SC is of great importance for the enhancement of coal mine safety and the prevention of mine fires. Fourier Transform Infrared Spectrometer (FTIRS) and Gas Chromatography (GC) have been used to analyse the index gases of coal in real time and offline (in the laboratory) to monitor SC conditions [93]. The products of the spontaneous combustion of coal are regular and measurable, so CO, C2H4, C2H2, and other gases are used as index gases for predicting SC in China [94]. The occurrence of CO corresponds well with the characteristic temperature of low-temperature oxidation of coal and is therefore the most widely used prediction parameter at present [95]. Determining the optimal algorithm and prediction model for the relationship between CO and other gases is crucial for predicting the spontaneous combustion of coal [96].

The index gases of coal SC are sometimes referred to as indicator gases or mark gases [97]. They can be divided into two groups, the majority (basic) and minority (additional) gases, as presented in Table 4-1.

Table 4-1 Majority and minority index gases [97]

Group	Index Gases
Majority (Basic)	CO, CH_4, CO_2, and O_2
Minority (Additional)	C_2H_6, C_3H_8, iso-C_4H_{10}, n-C_4H_{10}, C_2H_4, C_3H_6, C_2H_2, and H_2

Although only some components of the above are used for coal SC forecasting [98], in recent years, both majority gases and minority gases are required in most countries. For instance, in Poland, the assessment of minority gases is recommended [99]. In the Czech Republic, the State Mining Authority has mandated the monitoring of both the majority and minority of gases in their entirety under specific conditions in underground mines of the Ostrava-Karvina Coal field and China, CH4, C2H6, C3H8, iso-C4H10, n-C4H10, C2H4, C3H6, C2H2, CO, and CO2 are required to be monitored [93].

4.1.2 Gravity heat pipe (GHP)

A GHP is a passive heat-transfer device with extremely high thermal conductance [100]. The GHP has been widely used to effectively enhance the heat dissipation efficiency and impede heat accumulation of heat in coal piles, which has the tendency to lead to SCC. It also has the advantages of large heat transfer and good isothermal performance [101]. A typical example referred to often is the ability of the GHP to effectively enhance the stability of railway basements along the Qinghai-Tibet railway [102].

The functional principle of the gravity heat pipe includes the following after installation

(i) The evaporating end of the heat pipe starts to run driven by the oxidation heat inside the coal, making the working medium heated and gasified.

(ii) Under the action of pressure difference, the gaseous working medium rises to the condensing end of the heat pipe.

(iii) The working medium exchanges heat with the surrounding environment in the condensing section, cools and liquefies, then returns to the evaporating end of the heat pipe under the action of gravity, and then absorbs heat and evaporates again to complete the cycle [102, 103].

In this way, the oxidation heat inside the coal pile can continuously be extracted in the form of liquid phase transformation of the working medium of the heat pipe, thus rapidly diffusing the heat accumulation in the deep part of the coal pile and avoiding SCC.

Zhang et al. studied the transferring heat performance for controlling the SC in coalfield of heat pipe and found that, when the heat source temperature is higher, there is a greater cooling rate inside the coal pile [101].

4.1.3 Heat inhibitors

Considering the complex structure of coal, selecting an efficient chemical inhibitor to retard or prevent its SC remains a challenging task [47]. Among China’s state-owned collieries, 56% of the mines have been jeopardized by the combustion, which leads to huge personal casualties, economic losses, and massive environmental contamination [104, 105]. Heat removal systems such as ventilation equipment, sprinklers, or a supplement of liquid nitrogen are inadequate to holistically mitigate the SCC concerns facing the mine industry [106, 107]. The application of inhibitors decreases the concentration of readily available oxidized functional groups on the surface of coal [108]. Chemical inhibitors are widely used to prevent or extinguish coal mine fires and have been applied effectively for this purpose [47].

At present, a wide range of inorganic salts such as MgCl2, CaCl2, and NaCl have been considered for use in SCC inhibition [109, 110]. These inhibitors retard coal oxidation solely by building an impedance to oxygen and by the adsorption of water. As a result, these compounds typically exhibit low efficiency and short active lifetimes [47].

Tsai et al. [111] studied five inhibitors including; Zn/Mg/Al ‑ CO3 layered double hydroxides (LDHs), thermosensitive hydrogel (P(NIPA ‑ co ‑ SA)), diammonium phosphate ((NH4)2HPO4), d sodium phosphate (Na3PO4), and magnesium chloride (MgCl2) and found out that, Zn/Mg/Al ‑ CO3 ‑ LDHs, P(NIPA ‑ co ‑ SA), and (NH4)2HPO4 exert substantial inhibiting effects on anthracite and coke coal [111]. Distinctively, P(NIPA ‑ co ‑ SA) was altered during the liquid ‑ to ‑ gel phase, which isolated the oxygen from the coal surface and produced an endothermic reaction that decreased the environmental temperature; this reaction further inhibited SC [111]. However, MgCl2 promoted a combustion reaction and reduced the apparent activation energy of the coal, thereby increasing the risk of SC [111].

Antioxidants have also been employed in the fight against SCC to hinder and terminate the chain reaction of SCC by investigating the inhibitory effect of the gas generated. Based on different concentrations and dispersions, Yu Shuijun concluded that, after applying dispersant, the dispersion degree of antiager A in water increased, and the inhibition effect of resistance was improved, as evidenced by studying the amount of CO production during the process of coal low-temperature oxidation with antiager A [112]. Ma [113] studied the sustained inhibition effect of complex inhibitors of acrylic acid and ascorbic acid on five kinds of coal samples and reported that the complex inhibitor has the characteristics of eliminating heat accumulation and preventing free radical chain reaction. Dou [114] studied the inhibition effect of tea polyphenol on coal SC and believed that the inhibition was ascribed to the inhibition of peroxide radicals.

Coal can produce a variety of gases (CO, CO2, C2H4, C2H2, etc.) in the process of oxidation; the relationship between the minimum temperature, the gas generation, and coal temperatures varies with different coal samples [115, 116]. Therefore, the production of these gases can basically and accurately reflect the degree of coal SC, and then reflect the inhibition effect of antioxidants.

4.1.4 Foaming gels

A foamed gel is a kind of gas polymeric dispersing substance consisting of foam agent, gelling agent, cross-linker, and water, which was first used in petroleum exploitation to reduce the fluidity of the water phase and liquid phase, thus achieving a good sealing effect [95]. Foaming gel can also be grouted into the gob to narrow and stop the movement of the oxidized zone in the working face of a gob prone to SCC [117].

4.1.5 Grouting

Various literatures have reported on the development of a technology that makes use of cellular (foam-containing) grout to alleviate coal fires from the perspectives of prevention, control, and extinguishment. The variable combination of Portland cement, waste fly ash, sand, and special foams creates a highly easy flow, high-heat resistant grout that is used to simultaneously manage each of the three necessary fire elements: fuel, oxygen, and heat [118]. Grouts applied encapsulate burning material, thereby quenching the heat and fuel, and subsequently fill void spaces and passages, effectively acting on the sources of oxygen [118, 119].

In the past decade, fire-extinguishing methods mainly focused on mitigating air leakage and direct cooling, including grouting in layers, coverage, and excavation. Several economical grouting compositions employed in this approach included: clay and cement as the main materials [120], fly-ash grouting material [121], and a mixture made by mixing fly-ash and loess in proportion 1:2(w/w) [122].

Narrow coal pillar mining technology is often used to reduce the pressure on the underlying coal seam and to maximize the mining efficiency of coal resources. However, with the high gas and SCC, this technology can easily cause a gas and SCC composite disaster. To remedy this situation, Zhen et al. [123] formulated a new type of inorganic fire-extinguishing material (IFEM) that can go deep into the cracks of coal mass to seal up the cracks and reduce gas exchange between the roadway and adjacent goaf. The IFEM embodies a lot of moisture in the interior, which can reduce the temperature of the coal mass through evaporation and heat absorption. The IFEM has the characteristics of high-water retention, strong fluidity, and strong flame retardant, which can inhibit the generation of free radicals in coal mass at both physical and chemical levels, prevent the spontaneous combustion of coal mass, and reduce the occurrence of composite disasters of gas and coal SC. Due to its excellent sealing properties, it can reduce the generation of new free radicals and accelerate the destruction of primary free radicals [123].

4.1.6 Mine Staff Training and Awareness Creation

Consistent training for coal mine personnel on safety protocols plays a crucial role in minimizing and averting incidents by fostering awareness. To guarantee that mine personnel follow safety protocols, effective monitoring and supervision are essential to minimize unsafe practices. Furthermore, implementing a thorough quarterly assessment and evaluation for mining companies and their personnel can address certain incidents stemming from negligence and inadequate operational practices that may lead to fires. Implementing both internal and external measures for quality control and assurance can enhance safety initiatives aimed at reducing SCC, ultimately helping to prevent coal mine fires. From a broader perspective, it is possible to create a national entity focused on monitoring quality control and assurance, tasked with developing and implementing policies aimed at anticipating and averting SCC that may lead to coal mine fires. Moreover, enhancing education and fostering ongoing awareness can help minimize other associated sources of heat and fire ignition.

Finally, an extensive yearly assessment should be carried out to address key advancements in the sector, along with safety and risk management concerning SC and its effects on public health and the environment, including vegetation and climate change, to inform policy development. A schematic diagram is illustrated in Fig. 4-1, showcasing a proposed concept focused on preventing coal mine fires. This concept emphasizes the importance of training, raising awareness, conducting evaluations, and ensuring proper supervision and monitoring.

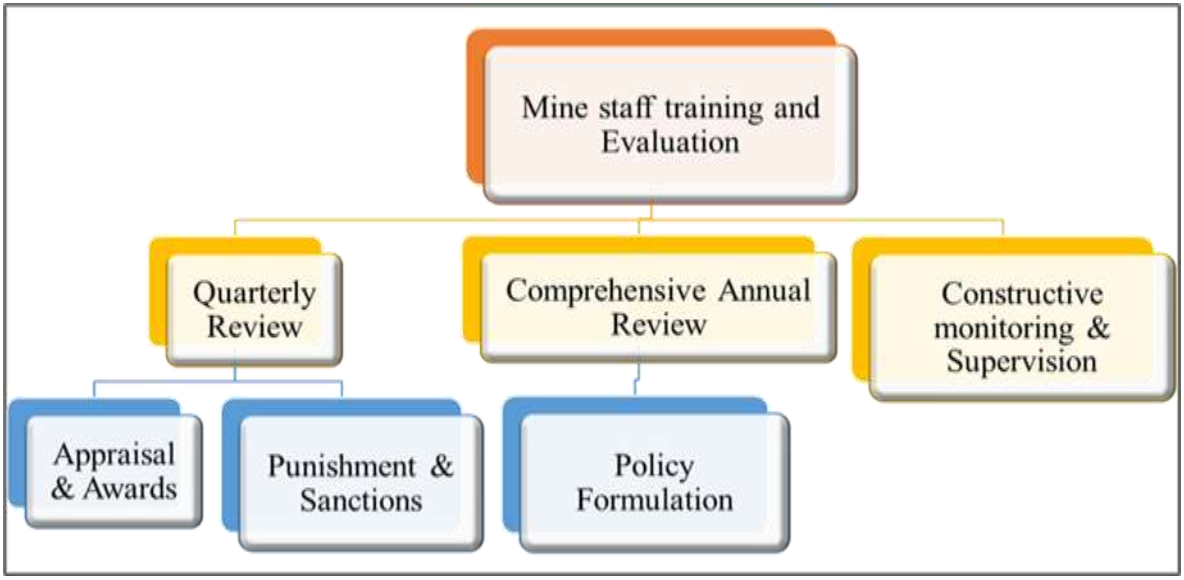

Fig. 4-1 Administrative and managerial proposed concept for coal mine fire prevention

4.2 Control of Coal Mine Fires

Mining companies may not prioritize the management of mine fires, yet given their inevitability, significant progress is essential to reduce the risks associated with these dangerous events. Here are two efficient techniques utilized for controlling mine fires.

4.2.1 Three-Phase Foam

Challenge:

A serious gas explosion occurred on October 24, 2003, in the Baijigou Coal Mine (BCM) of Ningxia Province in China, which resulted in sealing off the entire coal mine. The gas explosion occurred in the goaf of 2421−1 working face at 19:00 on October 24, 2003. Before 5:50 on October 25, 2003, more than 1000 gas explosions occurred discontinuously in the goaf.

Mine Background:

The BCM is one of the largest production bases of the most famous Taixi anthracite in China. The elemental analysis of the coal is characterized by low ash, sulphur, and phosphorus, having high mechanical strength, and a good capacity for gas absorption. The product is sold to over 20 countries in Europe, the Americas, and Asia [13]. The BCM is a highly gassy mine with the tendency of SC due to air inflow through the earth surface influenced by subsidence, and with the risk of dust explosion [124]. The full-mechanized mining and the full-mechanized caving methods were adopted at 4421−5 and 2421−1 working faces, respectively. The average operating depth of the mine is about 100 m.

Formulation and Infusion of the Three-Phase Foam

The preparation and injection of three-phase foam is explained and shown on Fig. 4-2.

Fig. 4-2 Three-phase foam preparation and injection into the underground fire zone, modified from [13]

Prevention:

A three-phase foam, made up of non-combustible material (mud or fly ash), inert gas (nitrogen), and water, was employed to control and extinguish the underground fire. Due to lack of access to the fire source and the sealing of the entire mine, the formulated three-phase foam was profusely infused into the mine workings from the surface borehole drilled by the T685WS gadding machine, made by Schrammin Corporation, USA [125] as shown in Fig. 4-3 stacking the foam, which rapidly covered the underground fire area.

Fig. 4-3 Left: Drilling T685WS gadding machine and Right: Boreholes connected with injection pipes on the surface of the mine [13]

Results and Inference:

After grouting, the mine was partially recovered by November 2003. The working face began production on December 24, 2003, while the 2421−1 full-mechanized caving face was unsealed successfully on September 28, 2004. Full production recommenced on December 6, 2004. This implies that the three-phase foam was very efficient in quenching the underground fire that emerged from over 1000 explosions.

4.2.2 Novel MS/CMC-Al3+ [1]

Innovation:

To utilize coal mine sludge (MS), reduce material cost, and prevent surface environmental pollution coupled with metal element contamination of water resources near landfill by applying the traditional treatment method of MS [126], Ren et al. [1] prepared a novel MS/CMC-Al3+ fire prevention and extinguishing material by mixing MS with sodium carboxymethyl cellulose (CMC), polyaluminium chloride, and citric acid.

MS/CMC-Al3+ Formula:

Step 1: A certain amount of GDL is dissolved in a beaker containing distilled water and stirred until the GDL is completely in solution.

Step 2: CMC is then added to the GDL solution, heated and stirred at the same time using a magnetic stirrer until CMC is fully dissolved (operating condition: 10 min at 40 oC).

Step 3: MS is slowly added to the solution and stirred until MS is evenly distributed.

Step 4: A certain amount of prepared crosslinking agent was uniformly mixed with the resultant solution and allowed to stand until the system gelatinized. All the above operations were carried out at room temperature (about 25 oC) except step 2. The graphical experimental procedure is presented in Fig. 4-4.

The amounts of the components used in the preparation of the gel are shown in [1]. The concentration gradients for each group of materials were estimated, and orthogonal groups were obtained by designing groups with good results. The preparation process of the AlCit crosslinking agent was obtained from the literature [127].

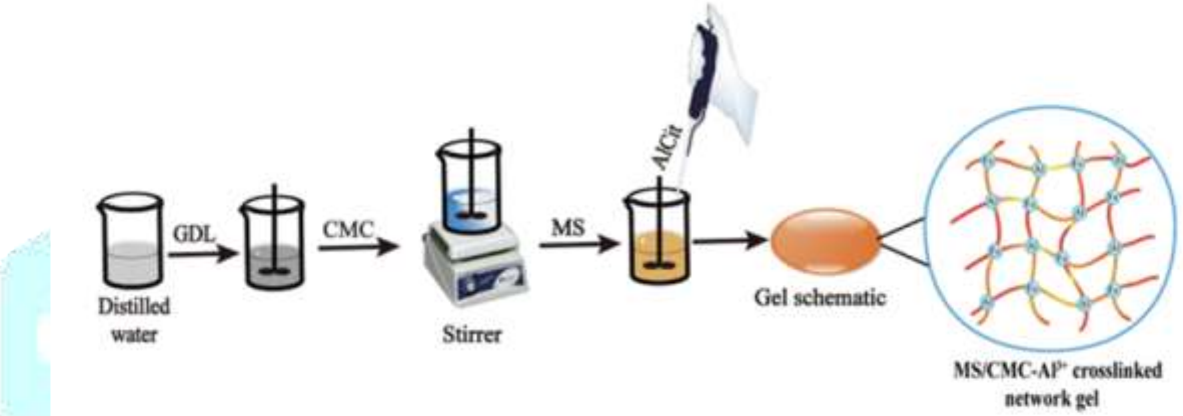

Fig. 4-4 Preparation process of MS/CMC-Al3+ gel [1]

MS/CMC-Al3+ Gel Gelation and Fire Prevention Mechanism

To comply with sewage discharge standards, coal mines modify the pH of wastewater to reach neutrality through the addition of acid or base. In a similar manner, the treatment of mine sewage involves the use of hydrolysed polyacrylamide (HPAM), which acts as a flocculant, alongside polyaluminium ferric chloride (PAFC), a coagulant, to effectively separate the solids from the liquids in the sewage. The modified acid-alkaline conditions facilitate the crosslinking of HPAM with Al3+ and Fe3+ in PAFC. The resulting mixture is fundamentally a blend of gel along with various elements such as coal, rock powder, and more. It was suggested that the metal ions engage in the cross-linking reaction not as simple ions, but rather as complex ions featuring multi-nucleus hydroxyl bridges and coordination with -COO, leading to the formation of a comprehensive network structure within the system.

The process of gelation in MS/CMC-Al3+ involves the crosslinking of HPAM and CMC using Al3+ and Fe3+ as cross-linking agents, resulting in the formation of an interpenetrating polymer network characterized by a high degree of cross-linking.

Results and inference:

MS: CMC: AlCit (aluminium citrate): H2O = 15:1:4:35, the MS/CMC-Al3+ gel exhibited the highest compressive strength and the most effective inhibitory impact. The integration of Raman spectroscopy and FTIR spectroscopy revealed that Al3+ and Fe3+ interact with HPAM and CMC to create a robust interpenetrating network gel, characterized by exceptionally strong cross-linking forces among them.

SEM analysis reveals that the HPAM-Al3+/Fe3+ gel greatly enhanced the compactness of the surface structure of MS following secondary crosslinking with CMC. The EDS-Mapping analysis reveals a uniform distribution of MS, CMC, Al3+, and Fe3+ within the MS/CMC-Al3+ gel, indicating that the HPAM-Al3+/Fe3+ gel has achieved complete cross-linking with CMC.

The inclusion of MS/CMC-Al3+ gel notably reduced the oxidation of coal, leading to a decrease in the production of CO and CO2, thereby serving a crucial inhibitory function. The creation of MS/CMC-Al3+ through the use of MS effectively minimizes pollution and expenses, while the resulting gel demonstrates outstanding fire prevention capabilities; thus, it serves as an exemplary new clean, fire-fighting material.

V. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Mine fires represent one of the greatest threats to those working in the underground coal mine environment. These threats have a global impact in the following forms;

(i) The economic cost on the world economy is substantial, including the management of fires, the rehabilitation of sealed coal mines, the depletion of important coal resources, and the compensation for fatalities, both deceased and surviving.

(ii) Environmental impacts include the emission of natural gases (such as CO and H2S), greenhouse gases (including CH4, CO2, SO2, and NOx), PM2.5, and condensate by-products into the environment, which result in health risks, destruction of faunal and floral ecosystems, and exacerbate human suffering due to heat, subsidence, and pollution.

(iii) SCC is the primary catalyst of coal mine fires, and addressing this issue would significantly diminish the prevalence of subterranean fires. Nonetheless, more effort should be directed towards prevention rather than management of coal mine fires. Similarly, attention should be directed towards addressing mechanical, electrical, natural, and anthropogenic causes of mine fires to mitigate fire breakouts.

(iv) Cost-effective strategies for the prevention, detection, and extinguishment of concealed coal fires in subterranean work environments must be developed through the application of contemporary foam, liquid nitrogen, and emerging firefighting technologies, such as the three-phase foam technology initiative.

5.2 Recommendations

An urgent need exists to augment safety regulations and implement an independent coal mine safety monitoring system to enforce the current legislation and standards. This strategy facilitates the accountability of offenders while incentivizing compliance via evaluation.

Consistent safety training, assessment, and awareness initiatives may significantly mitigate, if not entirely prevent, coal mine fires.

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ABBREVIATIONS

AlCit	(Aluminium Citrate)	MS	Mine Sludge
CMC	Sodium Carboxymethyl Cellulose	NGs	Noxious gases
FTIRS	Fourier Transform Infrared Spectrometer	OSM	Office of Surface Mining
GHGs	Greenhouse Gases	PM	Particulate Matter
GC	Gas Chromatography	$PM_{2.5}$	Mass of particles with aerodynamic diameters < 2.5 μm
GHP	Gravity Heat Pipe	PAFC	Polyaluminium Ferric Chloride
HPAM	Hydrolysed Polyacrylamide	SCC	Spontaneous Coal Combustion
JCF	Jharia Coalfield	SC	Spontaneous Combustion
MEMR	Ministry of Energy and Mineral Resources		